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RAPID COMMUNICATION

Manipulation of superconducting qubit with direct digital synthesis*

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We investigate the XY control and manipulation of the superconducting qubit state using direct digital synthesis (DDS) for the microwave pulse signal generation. The decoherence time, gate fidelity, and other qubit properties are measured and carefully characterized, and compared with the results obtained by using the traditional mixing technique for the microwave pulse generation. In particular, the qubit performance in the state manipulation with respect to the sampling rate of DDS is studied. Our results demonstrate that the present technique provides a simple and effective method for the XY control and manipulation of the superconducting qubit state. Realistic applications of the technique for the possible future scalable superconducting quantum computation are discussed.

Keywords: superconducting qubit, direct digital synthesis, arbitrary waveform generator

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1. Introduction

Quantum computing, which requires controlling highly complex and entangled quantum states, holds the promise for applications in various aspects like cryptography,[1–3] big data searching,[4,5] quantum artificial intelligence,[6,7] and quantum chemistry.[8,9] Among many of its implementation schemes, the superconducting quantum computing (SQC) has attracted much attention and becomes one of the most promising solutions to the practical quantum computing. With further development of SQC in recent years, intense researches on the superconducting qubits have been carried out to achieve the quantum error correction,[10–12] simulation of many-body physics,[13,14] and quantum supremacy,[15,16] which lead to the so-called noisy intermediate scale quantum computing with 50–100 qubits possibly able to perform tasks that surpass the capabilities of today's classical computers.[17,18]

In the SQC, as the number of qubits increases, more and more controlling and characterization instruments such as arbitrary waveform generator (AWG), microwave source, and some other microwave devices are used to realize the manipulation of the qubit state. Synchronization and phase lock between these instruments, and the calibration of some microwave components will become challenging since they will indeed affect the performance of qubit and gate fidelity,[19–21] both of which are essential in the SQC. Therefore, the simplification and optimization of the measurement instruments will be crucial for the scalable SQC.

In the SQC experiment, the XY positional control of a superconducting qubit (rotation around X/Y-axis of Bloch sphere) is usually realized by the combination of a microwave source, two channels of a digital-to-analog converter (DAC) with sampling rate of about 1 GSa/s, an in-phase quadrature (IQ) mixer, and corresponding amplifiers of intermediate frequency (IF) and microwave frequency. The continuous wave generated from the microwave source is put into the local oscillation (LO) terminal of the IQ mixer, modulated by the IF signals at the I/Q terminals which are output from DACs, and then applied to the qubit from the RF terminal (Here we name this approach as mixing technique). In this technique, it is known that there exist a series of shortcomings from the IQ mixer such as the presence of mirror frequency, microwave leakage, and imbalance of IQ arms. Although these negative influences can be largely eliminated by deliberate and careful design of the pulse shape, some noises and uncertainties can hardly be avoided effectively for the IQ mixer.

In order to avoid these shortcomings, it is natural to use direct digital synthesis (DDS) to define and output the microwave pulse signals directly so that the above described complex mixing processes are not required. This technique is much simpler and straightforward and could be useful in the SQC experiment, especially considering the increasing number of qubits employed in the future. However, unlike the ana-

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log signal produced by the microwave source, the microwave produced by DDS is a digital signal with its quality limited by the sampling rate, etc. and their influence on the qubit performance is unknown. In the previous studies,[22] Raftery *et al.* have used DDS to control superconducting qubits and carefully studied the phase noise of DDS. Although the method of DDS is feasible, some problems remain unclear. Does the DDS method affect the decoherence time and fidelity of the sample? And how high of the sampling rate can meet the measurement needs of the sample? It is well known that high sampling rate (over 65 GSa/s) DDS is very expensive. In practical applications, due to the price factor, the sampling rate is not as high as possible, and should balance the performance and price.

In this paper, we present an experimental study of achieving the *XY* control and manipulating the superconducting transmon qubit by DDS with a super-high frequency AWG (SHF-AWG, sampling rate 25 GSa/s) for the microwave pulse generation, instead of the traditional mixing technique using chain instruments. Signal noise, gate fidelity, and qubit performance are measured and compared with the results obtained from the mixing technique. Our results demonstrate that the DDS technique is a simple and effective way for the superconducting qubit manipulation with the sampling rate as low as 7 GSa/s while having a good qubit performance at the same time. The realistic applications of the DDS technique for the qubit state manipulation in the future scalable SQC will be discussed.

2. Experimental setup

To manipulate the qubit state, we need to use a series of microwave pulse signals with particular parameters required for the experiment. As shown in Fig. 1(a), there are four parameters to be controlled accurately: frequency, phase, amplitude, and pulse shape of the microwave signal. The frequency of the microwaves determines the reference frame of the quantum state moving on Bloch sphere (Fig. 1(b)), while the phase determines the rotation axis. For example, the quantum state rotates around the X-axis when the microwave input is a sine wave and the Y-axis when the driving microwave is a cosine wave, which has 90° phase difference. The amplitude and the length of the modulated microwave determine the Rabi frequency[24–26] and the rotation angle of the qubit state. With the calibrated microwave frequency, phase, and amplitude, we can precisely control the evolution of the quantum state in the Bloch sphere by adjusting the pulse length. According to different experimental requirements, different modulation shapes of microwaves will be selected. In order to prevent quantum state leakage to higher levels caused by anharmonicity of transmon,[27] the DRAG pulse[28] is usually used. To reduce the interference of high frequency components in the square pulse, the Gaussian shaped pulse is frequently used.

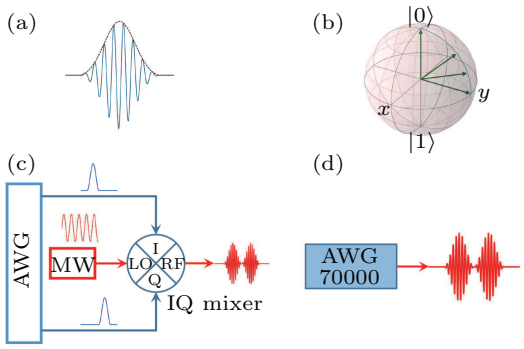


Fig. 1. (a) A sine wave modulated by Gaussian pulse shape (the black dashed line) into a wavepacket (the blue full line). Such a wavepacket is determined by four properties: frequency, phase, amplitude, and envelope shape. (b) The Bloch sphere. Quantum states can be represented by the vectors at the Bloch sphere (drawn with QuTiP[23]), and the modulated microwave wavepacket decides the quantum state trajectory of a qubit in the Bloch sphere. (c) Mixing technique schematic diagram. Continuous microwave generated by a microwave source (MW) is input into the LO terminal, and I/Q signals respectively generated by two channels of AWG are sent into the I and Q terminals, then the modulated microwave wavepacket is obtained from the RF terminal. (d) DDS technique schematic diagram. The microwave wavepacket is directly generated by SHF-AWG.

For the mixing technique, we use an AWG (Tektronix 5014C), whose sampling rate can be as high as 1.2 GSa/s, a microwave source (Rohde&Schwarz SGS100A), and an IQ mixer (MARKI 4509 LXP). Figure 1(c) shows the cable connection. We use the microwave source to generate the microwave, which is put into the LO terminal of the IQ mixer. Two channels of the AWG are respectively used to generate the I and Q modulation signals. Finally, the modulated signals are output from the RF terminal.

For the present DDS technique, as shown in Fig. 1(d), we use a SHF-AWG (Tektronix AWG70000 series) which has a sampling rate of 25 GSa/s and can directly generate about 12 GHz sine wave. Driving signals are edited and generated directly by SHF-AWG and then sent to the qubit chip to manipulate the quantum states. Background noise intensity and signal-to-noise ratio (SNR) of the signals generated by the two techniques are obtained by the spectrum analyzer, and displayed in Table 1. Through the comparison of the data, the DDS technique is far better than the mixing one in these two aspects.

Table 1. Comparison of background noise intensity and SNR between the two techniques.

	Backgorund/dBm	SNR/dB
Mixing technique	−49	35
DDS technique	−84	72

3. Results

The superconducting qubit used in our experiment is a transmon with its transition frequency of 7.129 GHz embedded in a three-dimensional aluminium cavity. The transmon

with a single Josephson junction is patterned using standard E-beam lithography, followed by double-angle evaporation of aluminium on a 0.5 mm silicon substrate with high resistivity ($\geq$ 10 kΩ·cm). The chip is diced into 3 mm×6.8 mm size to fit into the rectangular aluminium cavity with a TE101 mode resonance frequency of 9.052 GHz. The whole sample package is cooled in a dilution refrigerator to a base temperature of 10 mK. The dynamics of the system can be described by the circuit quantum electrodynamics (cQED) theory[29] which addresses the interaction of an artificial atom with microwave fields. The quantum states of the transmon can be controlled by well-designed microwave pulses as mentioned above. To readout the qubit states, we use a most-used microwave heterodyne setup. The output microwave is amplified by a high-electron-mobility transistor (HEMT) at the 4 K stage in the dilution refrigerator and two low noise microwave amplifiers at room temperature. Finally, this signal is heterodyned into 50 MHz and acquired by an analog-to-digital converter (ADC) card.

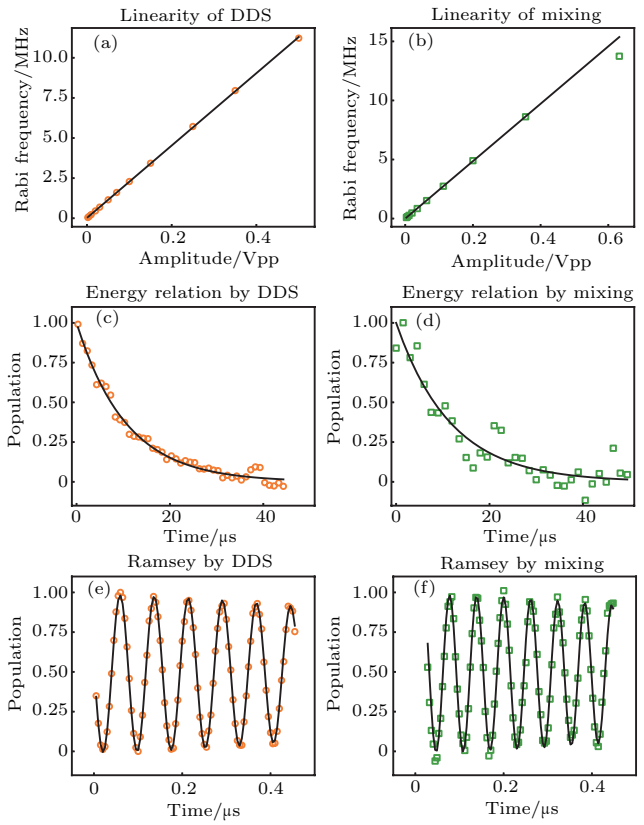


Fig. 2. (a), (b) The diagram of Rabi frequency versus AWG amplitude by the two techniques. The linearity of DDS is better than that of mixing. (c), (d) The energy relaxtion decay and (e), (f) Ramsey oscillation obtained by DDS and mixing techniques, respectively. The uncertainties of the DDS technique are smaller than the mixing one. Here colored markers and black line denote the experimental results and fitted curve, respectively.

Firstly, we test the performance characterization of the superconducting qubit. The modulated microwave pulse with the frequency of 7.129 GHz is defined and output directly from the SHF-AWG. Rabi oscillation, energy relaxation decay, and Ramsey oscillation experiments are carried out to get T_1 and T_2^*. Figures 2(a) and 2(b) show the linear relationship between the Rabi frequency and the amplitude of the microwave pulse obtained by the two techniques. The experimental results are well consistent with the theoretical prediction for DDS. For the mixing, the experiment results deviate from the linear prediction in the high voltage area resulting from the disadvantage of the IQ mixer. Figures 2(c)–2(f) show the results of relaxation time measurements and Ramsey oscillation. $T_1 \sim 11$ μs and $T_2^* \sim 15$ μs of the qubit are acquired by fitting the curves in Figs. 2(c) and 2(e), and these parameters are approximately equal to the results in Figs. 2(d) and 2(f) obtained by the traditional mixing technique. It suggests that the XY control of qubit using DDS will not affect the qubit performance.

Gate fidelity, which is the standard measurement of agreement between an ideal operation and its experimental realization, is a crucial characterization for qubit state operation. In order to test whether there are other hidden negative effects of the DDS technique, we measure the fidelity by using randomized benchmarking technique.[30–32] In this technique, the qubit is initialized in the ground state $|0\rangle$, and then applied by a randomized sequence of alternating Clifford and Pauli gates, here we choose I, X, and Y gates (Pauli gates). A final gate is applied to place the final state in either $|0\rangle$ or $|1\rangle$ so that the final measurement will be on an eigenstate of σ_z. As shown in Fig. 3, an exponential decay of the final state population is found as a function of the number of gates. After averaging and fitting the data, we calculate the average gate fidelity of each operation and it reaches 0.999, which is higher than that measured with the mixing technique (0.994). It suggests that the DDS technique is no less than the mixing technique in the fidelity comparison.

After the above comparison between mixing and DDS techniques, we find that the latter technique is simpler than the former one especially in instrument connection. It does not need to calibrate the IQ mixer and other microwave devices, and is more convenient for the qubit scalability.

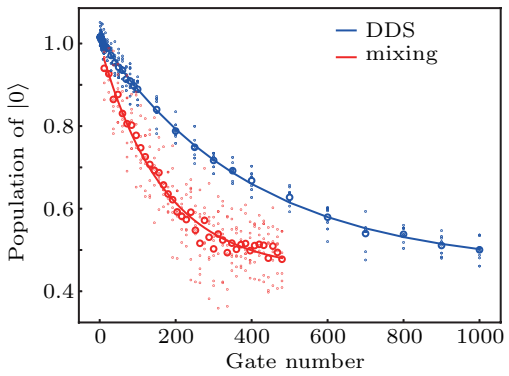


Fig. 3. Randomized benchmarking of Pauli gates (I/X/Y) obtained by DDS and mixing techniques, where the blue and red circles are the average of eight random sequences by different techniques. The gate fidelities calculated are about 0.999 and 0.994, respectively.

4. Discussion

Although the DDS technique can replace the mixing technique to achieve microwave manipulation of qubit, there still exists a disadvantage. As the sampling rate increases, the price of each channel increases. The price of a channel with 25 GSa/s sampling rate is about three times that of the devices and instruments used in the mixing technique. For transmon qubit, its usual transition frequency is around 3–7 GHz. To explore the needed sampling rate, we simulate the waveforms generated by the DDS technique with different sampling rates by rubuilding the waveforms with the nearest interpolation method and resampling them with a higher rate. Then we numerically calculate their equivalent amplitudes at the transition frequency by the fast Fourier transform (FFT) method. As can be seen from Fig. 4, as the sampling rate decreases, the equivalent amplitudes of the waveforms decrease, which indicates that in the manipulation of the quantum state, the reduction of the sampling rate causes the reduction of the Rabi frequency. Figure 5(a) shows the relationship of Rabi oscillation versus sampling rate. Even though the sampling rate is below the drive frequency of 7.129 GHz, the Rabi oscillation is still observed, because the waveform generated by the DDS technique is a step signal in the sampling interval, and this will introduce high frequency components. We calculate the FFT component at 7.129 GHz, which is directly related to the Rabi frequency, by the method above, and compare it with our experimental results, as shown in Fig. 5(b). The experimental results are in good agreement with the FFT simulation.

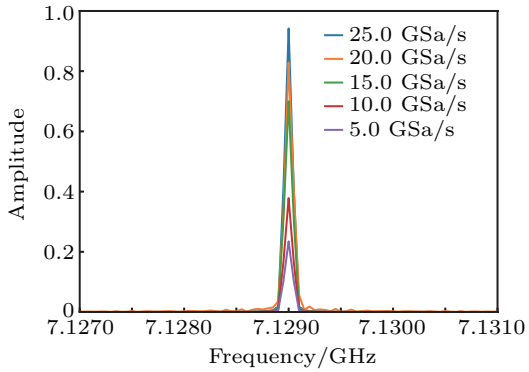


Fig. 4. FFT data of rebuilding waveforms to simulate that generated by DDS technique. The amplitude at 7.129 GHz decreases as the sampling rate decreases.

According to Nyquist–Shannon sampling theorem,[33] to restore the analog signal without distortion, the sampling frequency should be greater than twice the maximum component frequency f of the analog signal. If the sampling rate is less than $2f$, some of the highest frequency components in the defined signal will not be correctly represented in the digitized output. Therefore, in order to ensure accurate control of qubit, the DDS sampling rate should at least double the transition frequency of the qubit. In general, it is better to be more than 2.5 times.

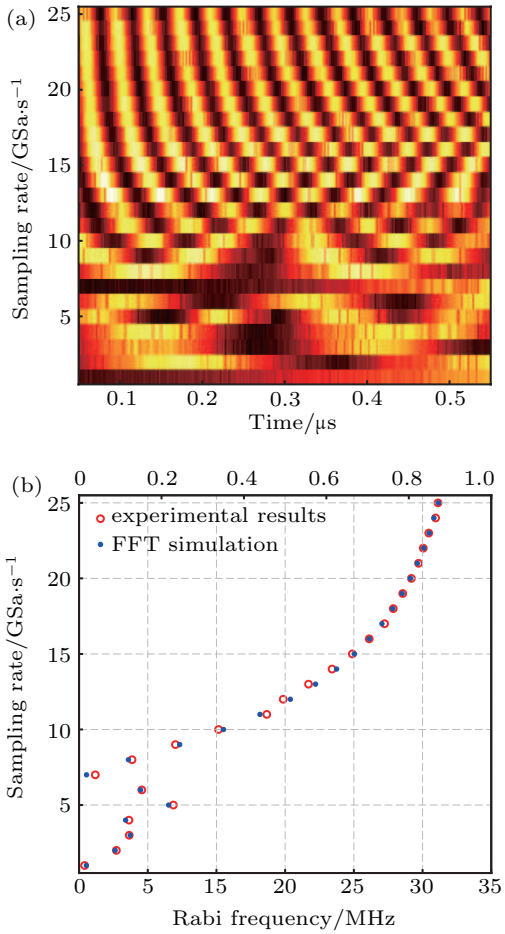


Fig. 5. (a) Image of Rabi oscillation versus sampling rate obtained by DDS technique. Even below the drive frequency, the Rabi oscillation is still observed. (b) Comparison of the experimental Rabi frequency and the amplitude of FFT simulation versus sampling rate. Red circles and blue dots denote the experimental and simulation results, respectively.

5. Conclusion

We have systematically explored the XY control and manipulation of the superconducting qubit state using DDS for the microwave pulse signal generation. Decoherence time, gate fidelity, and other qubit properties were measured and carefully compared with the results obtained by using the traditional mixing technique. The required sampling rate of DDS and the relationship between Rabi frequency and sampling rate were discussed in detail. Our results show that with the development of technology, the DDS technique can provide a new and simple approach for the qubit state manipulation in superconducting scalable quantum computing in future as the price of SHF-AWG with sampling rate exceeding 10 GSa/s reaches an acceptable level.

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