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Multiplexing Read-Out of Charge Qubits by a Superconducting Resonator *

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Wavelength division multiplexing (WDM) is widely used in modern optics and electronics. For future quantum computers, the integration of readout is also vitally important. Here we incorporate an idea of WDM to demonstrate multiplexing readout of charge qubits by using a single integrated on-chip superconducting microwave resonator. Two distant qubits formed by two graphene double quantum dots (DQDs) are simultaneously readout by an interconnected superconducting resonator. This readout device is found to have 2 MHz bandwidth and $1.1 \times 10^{-4}\,\mathrm{e}/\sqrt{\mathrm{Hz}}$ *charge sensitivity. Different frequency gate-modulations, which are used selectively to change the impedance of the qubits, are applied to different DQDs, which results in separated sidebands in the spectrum. These sidebands enable a multiplexing readout for the multi-qubits circuit. This architecture can largely reduce the amount of detectors and can improve the prospect for scaling-up of semiconductor qubits.*

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Quantum computation has a need for fault tolerant operation, which makes scaling up quantum systems a great concern. General quantum computation needs a large number of qubits. This is a great challenge for the architectural design, especially with the read-out technique. Traditional charge and spin qubits based on gate-defined quantum dots (QDs) were mostly read-out by a single electron transistor (SET) or a quantum point contact (QPC).[1,2] Recently, the application of radio-frequency resonant circuit techniques to single electron devices has led to the development of extremely fast and sensitive electrometers known as radio-frequency single electron transistors (RF-SETs),[3,4] but these devices cannot be simply integrated. Thus an on-chip approach to frequency multiplexing for the simultaneous read-out of scaled up qubit devices was performed to solve the problem.[5,6] Parallel to these developments, on-chip superconducting resonators were applied to couple QD circuits. So far, the QDs, made by carbon nanotubes,[7] GaAs,[8] InAs nanowires[9] and graphene,[10] can be dispersive read-out by resonators.

As in a superconducting system, a common resonator or dedicated electronics are required for each qubit that is used in manipulation and simultaneously read-out. It is therefore difficult to integrate a large number of qubits to create quantum processors. The technique of wavelength division multiplexing (WDM), widely used in modern optics and electronics, was applied to a superconducting system. This is called the frequency division multiplexing (FDM), which is the same technique used in WDM. With the FDM technique, the architecture of a single common microwave transmission line connected with a qubit chip employs resonators of different frequencies for individual qubits, which made multiplexing read-out and simultaneous manipulation of qubits[6] possible.

In this Letter, we report two graphene double quantum dots coupled with a single integrated on-chip superconducting microwave resonator, which can be simultaneously read-out by using the FDM method. We demonstrate that these two graphene double quantum dots do not interfere with each other when applying frequency multiplexing read-out at the same time. Similar approaches to frequency multiplexing have been demonstrated for distributed resonators in the context of kinetic inductance detectors,[11] superconducting qubits,[5,12] and RF-SETs. Our results show that it is possible to simultaneously read out many solid state qubits with a single read-out line, saving space in future scaled-up quantum devices.

Our sample, installed in a 38-mK base temperature dry dilution refrigerator, is shown in Fig. 1, which is the same sample we used in a previous experiment.[13] The resonator has a fundamental frequency of 6.35072 GHz and a quality factor of 3000. Two etched graphene double quantum dots (DQDs) separated by about 60 μm and made of a few layers of flakes are coupled to a superconducting reflection-line resonator (RLR)[10,13–16] through their sources.

The measurement circuit is illustrated in Fig. 2.

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A coherent microwave is supplied by a microwave generator (Agilent E8257D) and attenuated by about 60 dB before reaching the resonator. The on-chip half-wavelength resonator is coupled to the external microwave circuit via gap capacitors. The reflection signal is amplified first at 4 K and then at room temperature, producing an additional gain of 60 dB. An isolator is used to prevent the noise of the amplifiers and the environment from reaching the sample. After being amplified at room temperature, the signal was demodulated by an IQ mixer, then filtered and further amplified by a voltage amplifier (SRS SR560), and finally measured by using an oscilloscope (Tek DPO 72004).

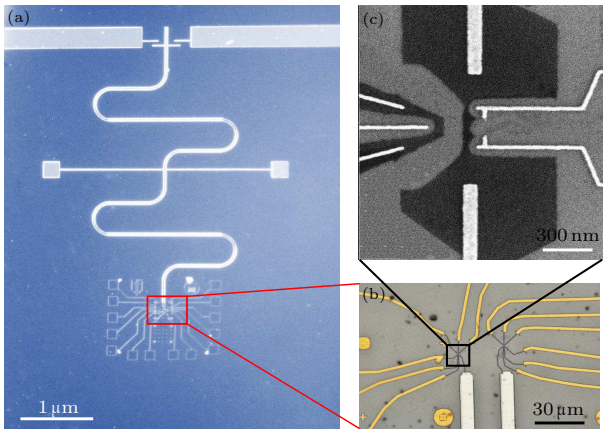

Fig. 1. (a) The half-wavelength reflection-line resonator is connected to two DQDs at one end of its two striplines, while the other end is used for the microwave input and output. (b) The two DQDs are separated by about 60 μm and are each coupled to one stripline through their source leads. (c) Scanning electron micrograph of a typical etched graphene DQD sample leads.

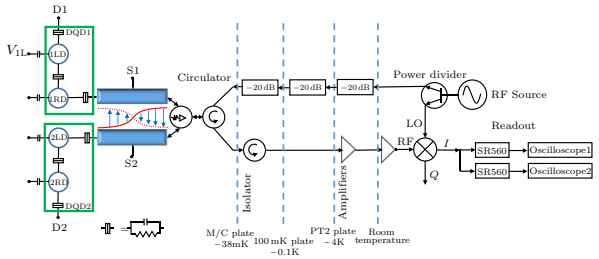

Fig. 2. Schematic diagram of the system setup.

To obtain a spectrum diagram, the reflection signal is directly measured by a spectrum analyzer (Agilent E4405B), which is working at a resolution bandwidth of 10 kHz as commonly used in most research.[1] Square wave modulations were applied to both left plunger gates of the two graphene DQDs, each with frequencies of 1.5 MHz (V_{1L}) and 2 MHz (V_{2L}) (the inset of Fig. 4). The result of the amplitude modulation spectrum shows that these two separate modulations hardly influenced each other. This is due to the fact that these two double quantum dots have very weak capacitive coupling through the superconducting reflection resonator. The coupling of one resonator can be generalized to a system with multiple quantum dots. By applying a different modulation to each quantum dot, the spectrum would give information from each quantum dot at the corresponding sideband.

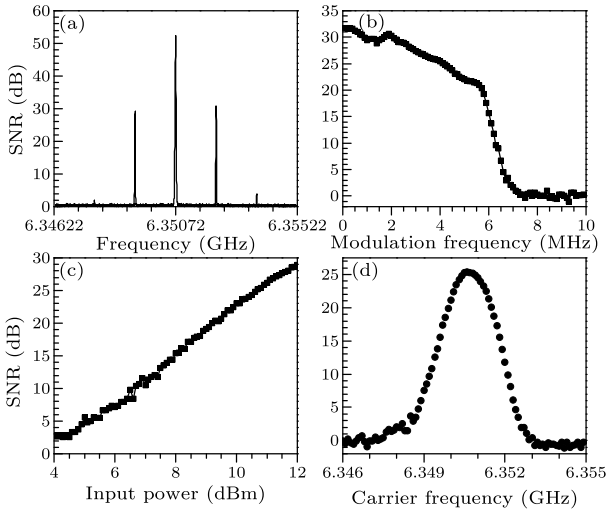

Fig. 3. (a) Amplitude modulation (AM) response of the resonator to 1.5 MHz and 2 MHz gate modulation at the same time. (b) SNR of the upper sideband as a function of the modulation frequency. (c) SNR of the upper sideband as a function of the input power. (d) SNR of the upper sideband as a function of the carrier frequency. All SNR measurements were made with a resolution bandwidth $\Delta f = 10$ kHz.

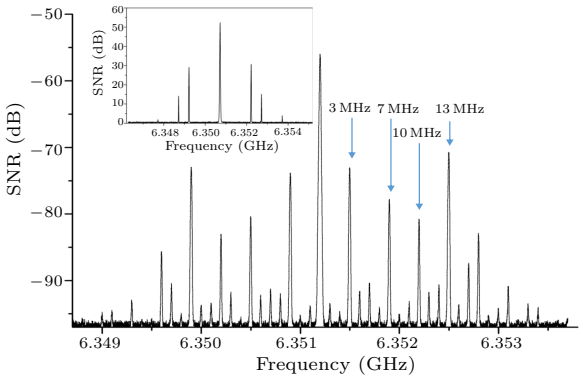

Fig. 4. The read-out spectrum of four modulations applied to the two graphene quantum dots. The inset shows the result of two modulations applied to the two graphene quantum dots.

To demonstrate this assumption, four different modulations with an amplitude of 200 mV and four frequencies of 3 MHz (V_{1L}), 7 MHz (V_{1R}), 10 MHz (V_{2L}), and 13 MHz (V_{2R}) were applied to the four plunger gates. The result presented in Fig. 4 is beyond our first estimate. As the plunger gates of the same double quantum dots have a strong capacitive coupling, such as V_{1L} and V_{1R} or V_{2L} and V_{2R}, this result shows interference of the spectrum signal. However,

the signals at the characteristic frequencies contain the information from each quantum dot. If the capacitive coupling between each modulation gates are weak enough, the spectrum diagram would be clearer.

The signal-to-noise ratio (SNR) as a function of modulation frequency is shown in Fig. 3(b). Using the SNR, we can estimate the 3-dB detection bandwidth to be about 2 MHz. Also, a charge sensitivity of about $1.1 \times 10^{-4}\mathrm{e}/\sqrt{\mathrm{Hz}}$ is given by $\delta q = \Delta q_{\mathrm{rms}}/(\sqrt{2\mathrm{BW}} \times 10^{\mathrm{SNR}/20})$.[4] Here the resolution bandwidth (BW) of the spectrum analyzer used to capture the signal was 10 kHz. The SNR is of the sideband, which was measured to be 36 dB at 1 MHz with 300 mV modulation. This result demonstrates that the sensitivity of our superconducting resonator is comparable to the best RF-QPC or RF-SET sensors, but yields a narrow measurement bandwidth.

To quantitatively analyze the reflected RF signal, we mapped the gap capacitive coupled half-wavelength resonator to a series lumped LC circuit model (see Fig. 5). With a characteristic impedance of $Z_0 = 50\,\Omega$, the resonator could be equivalent to an LC series resonant circuit consisting of capacitance $C \approx 1/Q\omega_0 Z_0 \approx 0.12$ fF and inductor $L = 1/\omega_0^2 C \approx 5.33\,\mu$H.

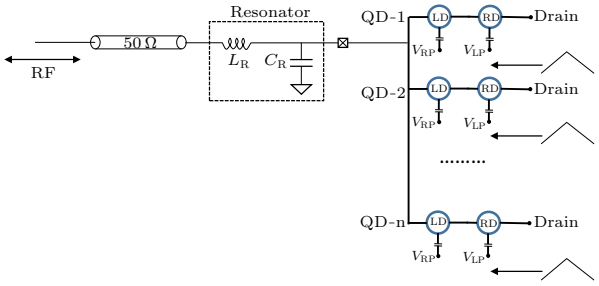

Fig. 5. A lumped circuit model of the resonator coupled to multiple DQDs. The gap capacitor coupled to a half-wavelength on-chip reflection resonator worked as a series resonant circuit model near resonance.

The reflection signal[17] can be simply expressed as

$$\begin{aligned} V_{\mathrm{ref}} &= V_{\mathrm{in}}[\Gamma_0 + \Delta\Gamma_1 \times \cos\omega_{\mathrm{m1}}t + \Delta\Gamma_2 \\ &\quad \times \cos\omega_{\mathrm{m2}}t] \times \cos\omega_0 t + n(t) \\ &= V_{\mathrm{in}}\Gamma_0 \cos\omega_0 t + V_{\mathrm{in}}\frac{\Delta\Gamma_1}{2}[\cos(\omega_0 - \omega_{\mathrm{m1}})t \\ &\quad + \cos(\omega_0 + \omega_{\mathrm{m1}})t] + V_{\mathrm{in}}\frac{\Delta\Gamma_2}{2}[\cos(\omega_0 - \omega_{\mathrm{m2}})t \\ &\quad + \cos(\omega_0 + \omega_{\mathrm{m2}})t] + n(t), \end{aligned}$$

where V_{in} is the voltage of the input signal to the resonator, Γ_0 is the original reflectance of the signal when no modulation signal is loaded, $\Delta\Gamma_1$ and $\Delta\Gamma_2$ are the reflectance variations of the two DQDs when the modulation signal is loaded, ω_{m1} and ω_{m2} are the circular frequencies of the two modulation signals, ω_0 is the carrier frequency of the resonator, and $n(t)$ is the noise signal of the whole circuit.

When compared with traditional QPC detectors, the RLR has a broader bandwidth. Using this advantage, we can realize rapid measurements after characterizing the basic parameters of the device. In this part, two different low-frequency triangular ramping voltages (17 Hz for DQD1 and 247 Hz for DQD2) were loaded into the two left plunger gates. After the reflected signal demodulated from the IQ mixer (see Fig. 2), the mixed information from the quantum dots can be separated by setting the cut-off frequencies of the pre-amplifiers (DC-30 Hz for DQD1, 100–300 Hz for DQD2). Both DQDs can then be individually and simultaneously read-out rapidly from the output signal of the two voltage amplifiers (SRS SR560) by using two oscilloscopes (Tek DPO 72004). As shown in Fig. 6, the honeycomb diagrams of the two DQDs take just 13 min, which is one-twentieth of the traditional measurement time. Both signals are read-out by the two triggered oscilloscopes simultaneously with the resonator working at 6.35072 GHz and a carrier power of −100 dBm. Also, a high Q factor gives rise to a high SNR and eventually results in the high contrast of the honeycomb chart.

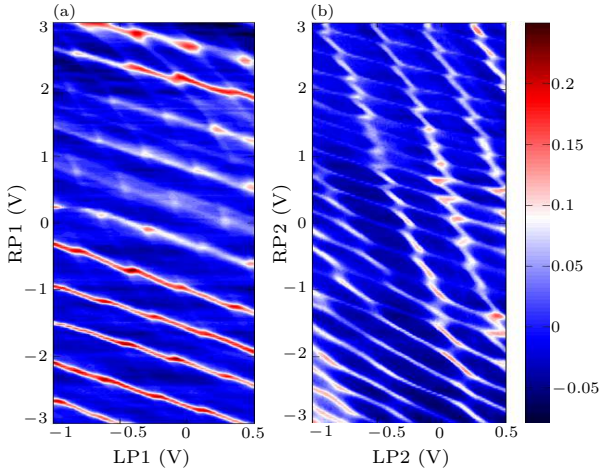

Fig. 6. Two different low-frequency triangular ramping signals loaded into the two left plunger gates. The delta signal at frequency of 17 Hz and amplitude of 300 mV was loaded to the DQD1 left plunger gate, and a frequency of 247 Hz and an amplitude of 300 mV were loaded into the DQD2 left plunger gate.

The half-wavelength on-chip resonator consisting of a pair of coupled micro striplines, which is known as the RLR, inspired us to make use of these two transition lines, each coupled with a DQD. This scheme makes simultaneous read-out of the two DQDs possible, in which the resonator can be used as frequency multiplexing[11] (MUX) circuits, radio-frequency LC circuits and dispersive sensors.

There is a difference between our multiplexing technique and the former technique that was used in spin qubits and superconducting qubits. The previous techniques[6,11,12] are passively frequency multiplexing

due to the fact that they all have different resonators connecting qubits with the transmission line. Ours is an innovative process where different modulations are applied to the qubits. The process can be thought of as a multi-frequency-locking technique.

In summary, we have characterized the bandwidth and sensitivity of a superconducting reflection resonator and reported a technique to simultaneously read-out multi-qubits using a single resonator. With the improvement of broad band superconducting resonators, this kind of setup can be extended to future structures with a large number of qubits, where all of the qubits can be simultaneously measured by a high Q resonator with separate frequency windows. Also, the simple design of this technique establishes a new direction for high-fidelity and high-integration qubit designs.

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