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Superconducting qubit network as a single microwave photon detector for Galactic Axion search

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***Abstract*—Experimental search of galactic axions requires detection of single photons in the microwave range. We work on a novel approach to detect single microwave photons based on a coherent collective response of quantum states occurring in a superconducting qubit network (SQN) embedded in a low-dissipative superconducting resonator. We propose a two resonators detector configuration with two parallel resonators without common part and with separated input and output terminals. The device consists of a low-dissipative resonator with embedded SQN in which microwave photons arrive ("signal resonator"), and a transmission line for measuring the frequency dependent transmission coefficient demonstrating resonant drops at the qubit frequencies ("readout resonator"). In comparison with T-type three terminal device recently proposed and investigated by us, the device with two resonators with separated input and output terminals doesn't contain common part of both resonators and exclude an unwanted noise from measurement readout circuits to the signal resonator. A layout of two resonators four terminal SQN detectors containing 5 flux qubits weakly coupled to a low-dissipative signal and readout resonator was developed and optimized. The samples were fabricated by Manhattan Al-based technology with Nb resonator circuits. The SQN detector was experimentally tested in terms of microwave measurements of scattering parameters of both resonators, and crosstalk properties. Comparison of experimental data with results of the simulations permits one to conclude that the electromagnetic conditions of the fundamental resonant peak of 8.5 GHz of both resonators aren't affected by the crosstalk phenomenon and their performances provided by the design remain not altered for correct device operation.**

***Index Terms*— Superconducting microwave devices, Josephson devices, superconducting resonators, superconducting detectors, microwave detectors, superconducting qubit.**

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I. INTRODUCTION

Photon detection in the optical domain is a well-developed technology established on different physical platforms [1], [2], [3] and was extended up to single photon detection limit for quantum computing application [4]. The main difficulty for the development of single-photon detectors in the microwave domain is the 5 orders of magnitude difference in photon energy with respect to the optical domain that, hence, requires operating at millikelvin temperature. This is the reason why the single microwave photon detectors have been only recently started to be investigated and are currently staying under development. The discovery of a usable single microwave photon detector would permit its immediate application in new classes of protocols for quantum sensing such as the microwave fluorescence detection of small electronic spin ensemble [5], quantum computing [6], [7] with new superconducting qubit readout based on a microwave photon counter [8], the robust generation of quantum states [9] and axion search based on haloscopes which is the general object of our research [10]. The axion is a pseudoscalar particle that was originally hypothesized by R. D. Peccei and H. Quinn to resolve the strong Charge-conjugation Parity symmetry (CP) problem of quantum chromodynamics (QCD) [11]. Axions are also well motivated dark-matter (DM) candidates with expected mass laying in a broad range from pico-electron-volts to few milli-electron-volts [12]. Standard axion conversion can takes place in a strong magnetic field into a microwave photons (Primakoff conversion) [13]. The power generated in this conversion process is extremely low about yJ (10^{-24}J) [14]. Sikivi proposed an axion detection scheme-"haloscope"- based on the Primakoff effect, which used a microwave cavity permeated by a strong magnetic field to resonantly increase the

number of photons produced by the decay [15].
The specific objective of our research activity is to develop and realize conceptually novel quantum limited Superconducting Qubit Network (SQN) detector capable to reveal single microwave photons for a photon frequency of ~10 GHz with the Heisenberg limit of sensitivity and the quantum limit noise with a view to apply it to search of galactic axions by means of standard "haloscopes". In contrast to [10] we propose a novel approach to detect extremely low energy microwave signal using SQN embedded in a low dissipative superconducting resonator. In the physics of Josephson effect, the connection of Josephson elements in an array results in appearance of novel collective quantum phenomena. Indeed, an array of simple Josephson tunnel junctions at certain geometrical configuration manifests geometry-driven Bose-Einstein condensation effect [16]. In an SQN embedded in a low dissipative resonator, coherent collective quantum states are established in the presence of a long-range exchange interaction between well-separated qubits which can be induced by the excitation (absorption) of virtual photons [17]. The collective quantum states have been observed in experiments on SQNs with flux qubits [18] and transmons [19]. In [20] we have studied theoretically the working principle of single photon detection based on an SQN embedded in a resonant cavity. We formulated the quantum-mechanical theoretical model in the general case of disordered interacting SQN. We obtained that an amplitude of the main resonance drastically increases as the interaction between qubits overcomes the disorder and the collective state is formed. In addition, we predicted that in the presence of a weak non-resonant photon field, the positions of resonant drops depend on the number of photons, i.e., the collective AC Stark effect takes place. In [20] we proposed a two resonators setup for practical realization of the detector that consists of an SQN embedded in a low-dissipative resonator (the so called "signal resonator") in which microwave photons arrive, and a transmission line (the so called "readout resonator") for measuring of the frequency dependent transmission coefficient demonstrating resonant drops at the qubit's frequencies. The major issue of this device is the optimization of the geometrical configuration of both resonators in such a manner to minimize the loss of single photons to be revealed, and to optimize electromagnetic noise in this microwave circuit. Recently we designed and fabricated T-type SQNs detectors with 10 flux qubits. The device were tested at ultra-low temperatures in terms of microwave measurements of scattering parameters and two-tone spectra. A substantial shift of the frequency position of the resonant drop of the transmission coefficient induced by the pump tone signal was observed by two tone measurements [14], [21]. In the T-type devise configuration half of the signal resonator is the path of readout resonator (three terminal device). The drawback of this configuration is that the common part of both resonators can imply an unwanted noise from measurement circuits to the signal resonator. In this paper we propose the device configuration with two parallel resonators without common part and with four terminals. We designed and fabricated a two parallel resonators SQN device. We carried out preliminary scattering parameter measurements at milli-Kelvin temperature. Experimental data are compared with results of simulation.

II. Sample Layout E Scattering Parameter Simulation

A. Sample Layout

The layout of the SQN with 5 flux qubits is shown in Fig.1a. The two resonators four terminal configuration was designed in such a manner to achieve a good sensitivity of the readout resonator to quantum states of the SQN, a good electromagnetic coupling between the signal resonator and the SQN, to satisfy the condition of absence of common part between two resonators and independent input and output terminals for both resonators. As a signal resonator we chose the simple transmission line with embedded 5 flux qubits (see Fig.1b - zoomed green part of Fig.1a).

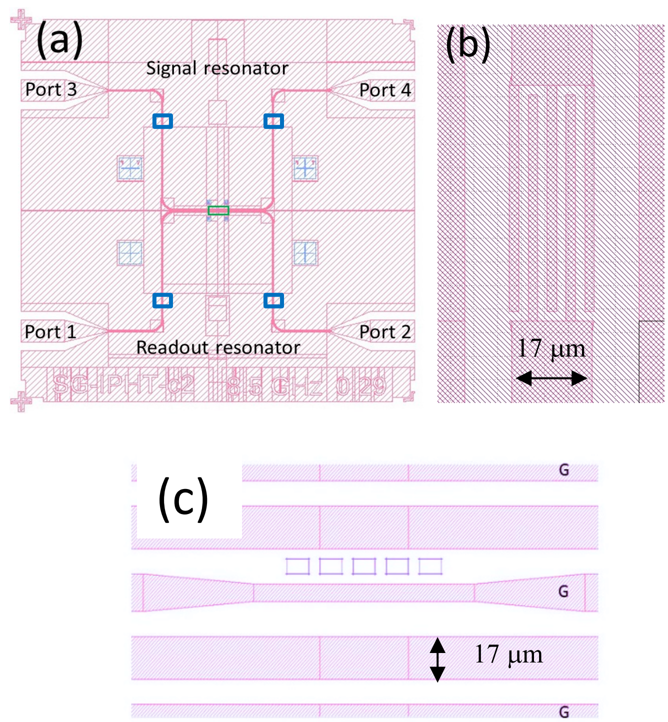

Fig. 1. (a) Layout of the two resonators four terminal SQN device. The chip dimension is 9 mm x 9 mm; squares in blu lines indicate the position of coupling capacitors; (b) input and output coupling capacitors on each resonator; (c) The zoomed central part of Fig.1(a) outlined by green rectangle. Letter "G" indicates the ground layer of the microwave circuits.

This type of resonator has demonstrated a good performance as a qubit state detector [22]. The geometry of the signal resonator was optimized for fundamental resonant frequency of 8.5 GHz. Each flux qubit of the SQN consists of a 9.7 x 5.68 μm^2 loop with four Josephson junctions (see Fig.1 b). This number of junctions is defined by the Manhattan technology used for Al-based Josephson junction fabrication. Three junctions are designed to have identical size of 0.15 x 0.15 μm^2

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while the fourth is scaled by a factor 0.8. Such geometrical parameters of the single flux qubit allow to reach the frequency spacing between the lowest two energy levels for single qubit about 8.5 GHz in external magnetic flux of $\Phi_0/2$ where Φ_0 is the magnetic flux quantum. The readout resonator has the identical geometry as the signal one but is inverted and has the common ground line with the signal resonator (see Fig.1 a). We note that the fundamental frequency of the readout resonator was chosen as 8.5 GHz the same value as the fundamental frequency of the resonant cavity of the "haloscope" of the INFN of Frascati, Italy, where the SQN detector will be installed in future for axion search experiment. We note that both signal and readout resonators are delimited by two capacitors of about 5 fF each.

B. Scattering Parameter Simulation

The simulations were done by the Sonnet Software v14.54 software. Starting from the original layout reported in Fig.1 a, a simplified version of the design was obtained removing all the unnecessary features like the markers and labels. Also, the 5 qubits were removed from the simulation. Since the hardware used for the simulation of the whole layout area of 9 x 9 mm^2

Layout imposes a constraint for the finest meshing of the structure of 4 x 4 μm^2, which is too coarse for the proper simulation of the coupling capacitors, these structures were simulated apart and later inserted in the original design as lumped data file components. For this purpose, an area of 100 x 100 μm^2 around the capacitors was removed and its response was simulated in the 4-12 GHz range (step of 0.05 GHz) exploiting a meshing of 0.25 x 0.25 μm^2.

For all the simulations reported in this paper the dielectric stack up was set as reported in Table 1, while the Nb superconducting film was simulated with a general film model imposing R_{dc}=0 Ω/sq, R_{rf}=0 Ω/sq, X_{dc}=0 Ω/sq and L_s=0.2 pH/sq [23].

TABLE I
SIMULATION PARAMETERS

Layer number	Material	Thickness [µm]	Relative permittivity	Dielectric Loss Tangent	Resistivity [Ω*cm]
Layer 3	Vacuum	1000	1	0	
Layer 2	Silicon	400	11.45 [24]	2.0×10^{-4} [24]	1.0×10^{5}
Layer1	Vacuum	1000	1	0	0

The whole layout was then simulated with a 4 x 4 μm^2 meshing, inserting in place of the four coupling capacitors an equal number of data file components.

The results of the simulations, in terms of scattering parameters magnitudes as a function of frequency, are reported in section III as paragraph C "*Scattering Parameter Measurements and comparison with results of simulation*s".

III. EXPERIMENT

A. Sample Fabrication

Two identical resonators are fabricated by depositing a 200 nm thick Nb film on a silicon substrate that is structured by Reactive Ione Etching (RIE). The flux qubits are made of Al Josephson-junctions fabricated by Manhattan-type fabrication technology. In comparison with the two-angle shadow evaporation technique the Manhattan technology allows the fabrication on wafer-scale, it doesn't require free standing, fragile resist mask and offers better reproducibility. Samples were fabricated with a Josephson critical current density of 80 A/cm² ensuring the simulated energy level splitting as required by the planned measurement protocols. Optical pictures of two resonators four terminal SQN devices with 5 flux qubits with four Josephson junctions are shown in Fig. 2.

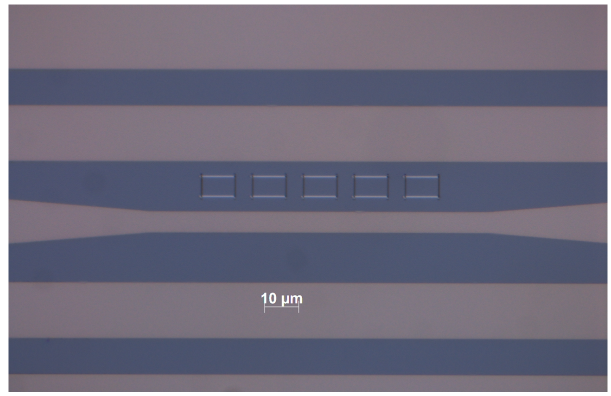

Fig. 2. Optical picture of two resonators four terminal SQN device with 5 flux qubits.

B. Experimental Setup

The two resonators four port SQN device was installed in a copper sample holder, that, in turn, was mounted on the coldest plate of the dilution refrigerator CF-CS110-500 from Leiden Cryogenics located at the INRiM's Quantum Circuit for Metrology Laboratory. During the experiment the base temperature was around 80 mK, the schematics of the cryogenic microwave measurement setup is shown in Fig.3.

The microwave setup provides a couple of identical input lines (A_1 and A_2) and a couple of identical output lines (B_1 and B_2). Two electro-mechanical cryo-switches (SW_1 and SW_2) permit to connect one input line and one output line to two either sample ports 3 and 4 or reference devices (a *Thru* and a -20 dB attenuator). Direct connection of the second input and output lines to sample ports 1 and 2 permits to carry out measurements of two port scattering parameters between different ports (S_{21}, S_{43}, S_{41}). The transmission coefficient S is measured by the ZNB20 Vector Network Analyzer 100 kHz-20 GHz Rohde & Schwarz.

The two input lines (i.e., A_1 and A_2) are stainless steel coaxial lines heavily attenuated at each plate of the dilution refrigerator to reduce the thermal noise at the ports of the sample. The sample ports are connected by superconducting coaxial cables (NbTi) to the output ports of two electro-mechanical cryogenic RF six-ports cryo-switches SW_1 and SW_2 (R5927B2141 from Radiall). For the sake of simplicity in Fig. 3 we report just three output ports of the six ones. Due to the lack of a reliable cryogenic calibration kit, for the reported measurements the *Thru* and the -20 dB cryogenic attenuator were used as a reference. Same length superconducting coaxial cables were used to connect both the ports of the sample resonators and the references to the switches. The output lines B_1 connects the IN port of the cryo-switch SW_2 with the room temperature interface while the output line B_2 connects the port 2 of the SQN device with the room temperature interface. Both output lines are realized with the same superconducting coaxial cables up to the 3K stage. The remaining stretch of the connections are realized with stainless steel coaxial cables.

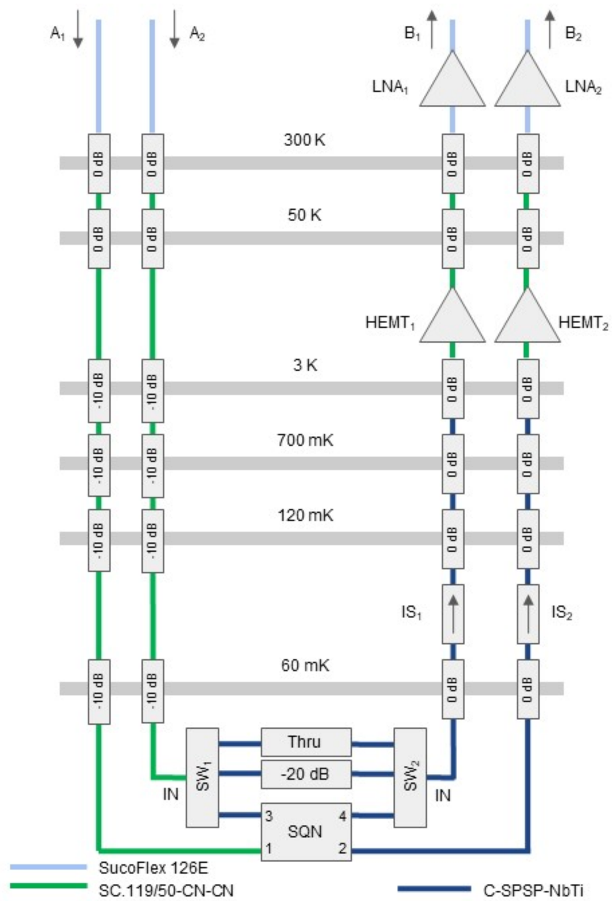

Fig. 3. Schematic of the microwave measurement setup.

As shown in Fig. 3, on the 3K stage are located two HEMTs (LNC0.3_14A from Low Noise Factory) that constitute the first stage of amplification of the readout line. To protect the SQN device from the backward noise generated by the HEMTs, a couple of circulators with -50 dB of isolation (LNF-CICICIC4_12A from Low Noise) are placed along both readout lines at the level of the 80 mK temperature plate. We note that the sample holder is provided by the superconducting magnetic coil for tuning the energy levels of flux qubits. Because the magnetic field was not used in the experiment reported in this paper, both the coil and the DC electrical lines, for current supply to the coil, are not reported in Fig.3.

C. Scattering Parameter Measurements and comparison with results of simulations

We characterized the two resonators four port SQN device in zero magnetic field at T=80 mK by measuring the scattering parameters -transmission coefficient S-of both signal and readout resonators and the crosstalk between them. Fig.4 reports raw experimental results of the transmission coefficient S as function of frequency f measured for the signal and readout resonators compared with results of simulations.

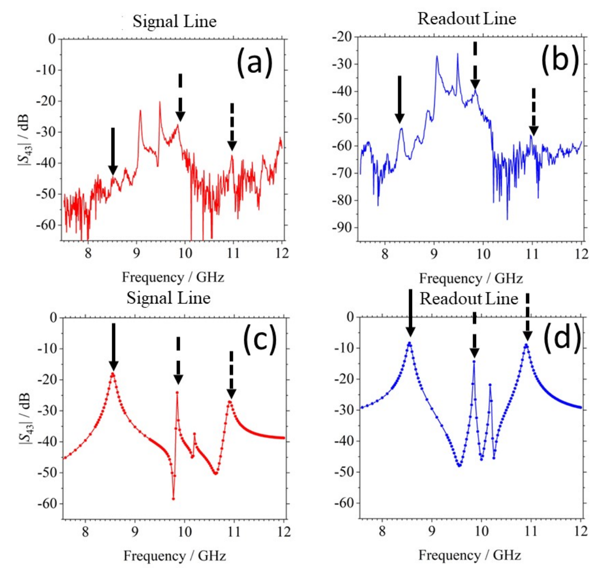

Fig. 4. Experimental dependencies of the transmission coefficient S on frequency measured for the signal resonator (a) and for readout resonator (b). Curves (c) and (d) are the results of simulation made for signal resonator and for readout resonator, respectively. The port numbering corresponds to the one depicted in Fig.1a. The arrows indicate the peaks experimentally observed and predicted by simulations.

We note that the port numbering in Fig. 4 corresponds to the one depicted in Fig.1a. The S_{21}(f) curve (Fig. 4a) of the signal resonator shows a clear peak at frequency 8.5 GHz as was defined by the layout design and confirmed by the simulations (Fig.4c). Besides the peak of 8.5 GHz, quite a number of resonant peaks and dips were recorded at frequency greater than 8.5 GHz. The experimental resonant depth at 9.6 GHz, resonant peaks of 9.9 GHz and of 10.9 GHz were predicted by the simulations (see arrows of Fig. 4a and Fig.4c).

The planar current density distribution within the layout was simulated at the reference frequencies of 8.55 GHz and 9.85 GHz (Fig.5). The label "Stimulation" in each of the panels in Fig. 5, indicates the port at which the signal is applied to generate the displayed distribution. A magnification of the current distribution within the central area of the layout is also provided for each frequency. Fig.5 shows that for frequency of 8.55 GHz the planar current density is mainly localized inside the resonator where the current is stimulated while for frequency of 9.85 GHz the current distribution extends up to another passive resonator. From this

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observation it is possible to conclude that the resonant peak of 8.5 GHz results from the resonant phenomenon in the signal resonator while the appearance resonant peak of 9.85 GHz (and also another high frequency peaks) is associated to the crosstalk effect. Fig. 6 reports experimental data of the crosstalk measurement (a) and result of the crosstalk simulations (b). Results reported in Fig 6 confirm the crosstalk nature of the resonant drop of 9.6 GHz and resonant peak of 9.9 GHz.

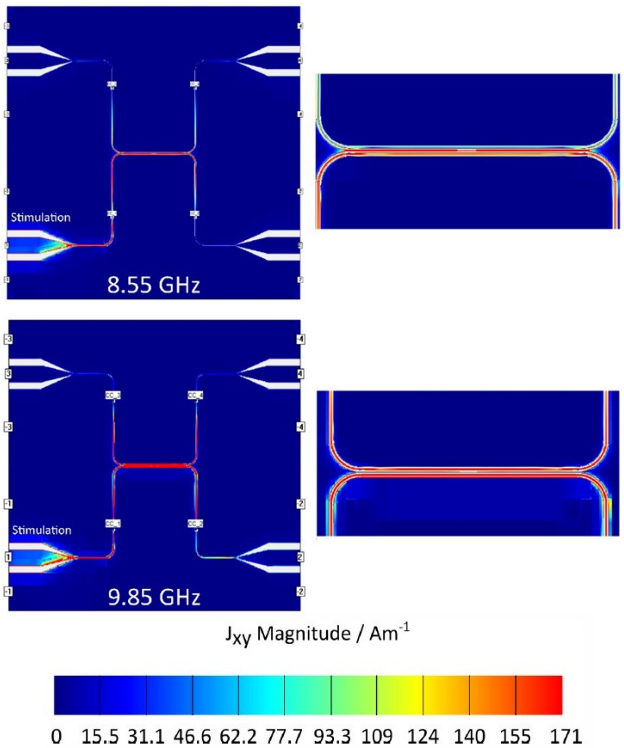

Fig. 5. The planar current density distribution within the layout at the reference frequencies of 8.55 GHz and 9.85 GHz. The label "Stimulation" indicates the port of the readout resonator at which the signal is applied to generate the displayed distribution. A magnification of the current distribution within the central area of the layout is shown for each frequency.

Because the resonant conditions of 8.5 GHz of the signal resonator seems to be unaffected by the crosstalk phenomenon, single photons with frequency of 8.5 GHz can be transmitted from input port to the SQN region without loss. The scattering parameter measurements and their analysis with the simulation results for the readout resonator are similar to the results for the signal resonator (see Fig. 4 (b) and (d)), the resonant conditions of 8.5 GHz are not affected by the crosstalk with the signal resonator and this resonant peak of 8.5 GHz of the readout resonator is suitable for detection of quantum states of qubits of the SQN. Further experiments are in progress to detect the SQN states applying an external magnetic field to tune energetic levels of the qubits. It is expected to measure resonance frequencies related to collective quantum states of the SQN.

V. Conclusion

We have investigated a two resonators detector configuration with two parallel resonators without a common part and with separate input and output terminals. In comparison with T-type three terminal device recently proposed and investigated by us [14], [21], the device with two resonators with separated input and output terminals doesn't contain common part of both resonators and exclude an unwanted noise from measurement readout circuits to the signal resonator. A layout of two resonators four terminal SQN detector containing 5 flux qubits weakly coupled to a low-dissipative readout and signal resonators was developed and optimized. The samples were fabricated by Manhattan Al-based technology with Nb resonator circuits. The SQN detector was experimentally tested in terms of microwave measurements of scattering parameters of both the single resonators, and crosstalk properties. From the comparison of experimental data with results of the simulations it is possible to conclude that the electromagnetic conditions of the fundamental resonant peak of 8.5 GHz of both resonators are not affected by the crosstalk phenomenon and their performances provided by the design remain not altered for lossless single photon transmission by the signal resonator and the effective qubit detection by the readout resonator.

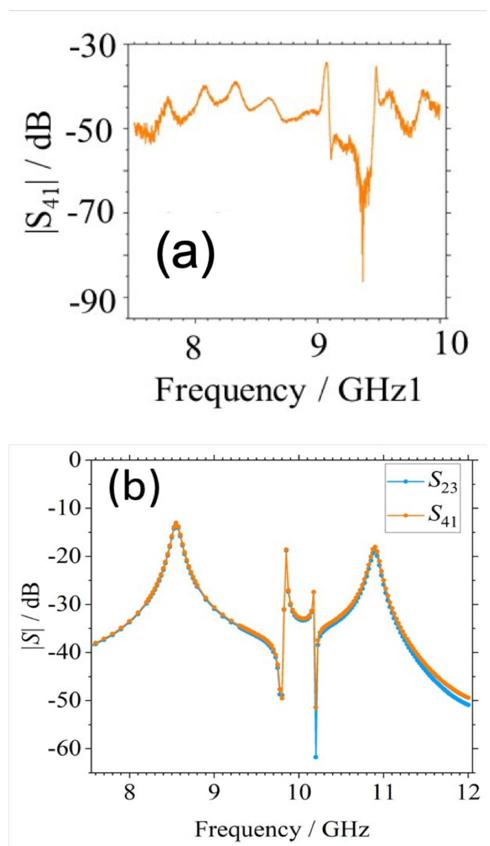

Fig. 6. (a) Experimental data of the crosstalk measurement; (b) Result of the crosstalk simulations.

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