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### ADVERTISEMENT



## Qubit dispersive readout scheme with a microstrip superconducting quantum interference device amplifier

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A flux qubit readout scheme involving a dispersive technique coupled to a microstrip superconducting quantum interference device (SQUID) amplifier has been tested experimentally. Thanks to the almost quantum limited noise of this amplifier at low temperature, this readout device is very promising for a design with actual qubits. Its proof of principle and low noise performance have been tested by simulating the qubit presence by applying a tiny flux change in the input SQUID. The resonant frequency of the amplifier is adjusted *in situ* with a varactor diode to approach the frequency of the tank circuit. Two operating modes (crossing or anticrossing regime) were identified. © 2009 American Institute of Physics. [DOI: 10.1063/1.3109793]

Many systems such as photons, ions, atoms, etc. are presently being considered to implement a quantum computer, each of them with their own advantages and residual challenges. Among these various possible building blocks lies one of the most macroscopic realizations of a quantum bit or qubit: a superconducting circuit. These electrical circuits such as flux qubits<sup>1</sup> can be viewed as engineered "atoms," which could benefit from the advantages of lithography to scale up the number of qubits in a system. Moreover, the coupling between two such qubits can be controlled and even switched off by the application of an appropriate superconducting current in a superconducting quantum interference device (SQUID) surrounding these qubits.<sup>2</sup> However, reducing the coupling with the environment, a source of decoherence, is still the main challenge for these qubits. In practice, the relaxation time T1 and the dephasing time T2 are currently too low to build a practical computer: they amount to a few hundreds and a few tens of nanoseconds, respectively, while about 10  $\mu$ s would be required. The difficulty arises from the need for the qubit to be isolated to the maximum from the rest of the world to stay coherent. But in order to access it such as for the readout process, connections have to be established between it and the outside world, therefore bringing sources of decoherence. In a realistic design, the same SQUID used to control the coupling is also used for the readout. In Ref. 2, an unshunted dc SQUID switching readout was used with the disadvantage that the SQUID changed to the dissipative state. Due to this switch, repetition rates in relaxation-sensitive measurements may be no faster than 1 kHz, in order to allow for the recombination of hot quasiparticles. The focus here is to improve the readout process by using a dispersive readout technique not generating heat and thus allowing much faster repetition rates. Such a dispersive readout, measuring a change in the dynamic inductance of the SQUID as it varies with the flux in the qubit loop enclosed, has already been realized in Refs. 3-5. However, the noise temperature of the amplifier used for the readout is critical. Here, a dispersive readout with the microstrip SQUID amplifier (MSA) (Ref. 6) is presented.

Indeed, in the 1 GHz range and at dilution fridge temperature, this amplifier is almost quantum limited<sup>7</sup> with a noise temperature of a few tens of millikelvin. This is about 20 times better than today's best GaAs cryogenic amplifiers, which have noise temperatures that cannot be made better than 1 K. Combining the MSA with a dispersive readout scheme would potentially offer not only a decrease of the measurement time of a qubit but also a means of limiting the coupling with the qubit, thus minimizing the source of decoherence due to the readout device.

To experimentally test the principle of a dispersive readout with a microstrip amplifier, a tank circuit composed of an input SQUID and two 20 pF capacitors (surface-mount high Q mica capacitors MC08, from Cornell Dubilier) have been built (see Fig. 1). The microwave readout pulse is sent from the left ( $V_1$  line, after the succession of a 49 dB attenuator at ambient and a 30 dB attenuator at 1 K), into the 220 nH inductor whose large impedance at microwave frequency avoids the quality factor of the tank being loaded with the 50  $\Omega$  line. The MSA (on another chip) is hooked by taping the two tank capacitors with a coupling capacitor of 2 pF. A 470 pF capacitor is used on the right to ac couple the output  $V_2$  of the MSA. The MSA is depicted here by a microstrip and a second SQUID side by side but in practice the microstrip lies on top of the SOUID washer with an insulating layer in between. Two high electron mobility transistor (HEMT) postamplifiers are subsequently used at 4 K and at ambient temperature with a total gain of 71 dB. A GaAs varactor diode (Macom MA46 serie and ranging from 40 pF at 0 V to a few picofarads at 13 V) is placed at the extremity of the



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FIG. 2. Transmission vs frequency curves obtained at 0.309 K and with the MSA OFF, for different input flux in the tank circuit SQUID ( $I_{F1}$ ). After the attenuators, the incoming power is -99 dBm.

microstrip in order to tune the frequency of the MSA.<sup>8</sup> Practically, the MSA (made in Ref. 9) consists of a Nb square washer ( $L_{self}$ =300 pH) with Nb/AlO<sub>x</sub>/Nb shunted junctions (capacitance estimated to 0.2 pF, shunt resistance is 13  $\Omega$ , and critical current  $I_0=8.5 \ \mu A$  per junction) above which (but separated by 400 nm SiO) lies the microstrip: an eightturn Nb coil (5  $\mu$ m large and 11 mm long). The input SQUID is in fact from the same batch as the MSA and is therefore very similar except that the microstrip is not used  $I_0=4.5 \ \mu A$  and in order to reduce the self-inductance (to about 15 pH) we deposited a superconducting ground plane on top of it (150 nm SiO+100 nm Nb). The length of the Al wirebonds was kept minimal, placing in each instance five wirebonds in parallel to reduce their stray inductance. dc current and flux bias lines permit bias the MSA at its optimum points ( $I_{b2}$  and  $\Phi_2$ ) as well as application of the right flux in the input tank circuit SQUID ( $\Phi_1$ ). For  $\Phi_1$  and  $\Phi_2$ , external coils were used. The input SQUID is the one which in practice would enclose the qubit that has to be measured. A change in the qubit that couples its flux in this SQUID would lead to a change of the order of  $10m\Phi_0$  in the SQUID, where  $\Phi_0 = h/2e \approx 2 \times 10^{-15}$  Tm<sup>2</sup> is the flux quantum. In order to perform the readout in say 100 ns, a flux noise relative to the input SQUID as low as  $3\mu\Phi_0/\sqrt{Hz}$  has to be achieved. For this test of principle of the readout device, a real qubit enclosed in the input SQUID has not been used but it has rather been verified that a change as small as  $10m\Phi_0$  applied to it by the dc flux biasing coil leads to a good sensitivity  $\Delta V_2/\Delta \Phi_1$  and the desired flux noise  $\Phi_{1N}$ . These tests were carried on at 300 mK in a charcoal-pumped <sup>3</sup>He cryostat.

Since the grounding of the washer of the MSA is not perfect (it is made via five small wirebonds in parallel), the microwave transmission although being low can still be detected if the MSA is turned OFF, as can be seen on Fig. 2. Here we only have a 10 MHz change in the resonant frequency  $f_r$  of the tank circuit going from  $\Phi_1 = \Phi_0$  to  $\Phi_0/2$ because the tank capacitors are located off-chip. This arrangement gives relatively large stray inductors due to the wirebonds and the surface mount capacitors. The resulting total stray inductance  $L_{\text{stray}} = 8$  nH reduces the change of the resonant frequency roughly given by

$$f_r = \frac{1}{2\pi\sqrt{[L_{\text{stray}} + L_J(\Phi_1)]C}}.$$
(1)

No dc bias current is applied to the tank circuit SQUID so the phase difference  $\delta(\Phi_1)$  is the same across each junction of the tank circuit SQUID. The Josephson inductance (per junction) amounts to

$$L_{J}(\Phi_{1}) = \frac{\Phi_{0}}{2\pi I_{0} \cos[\delta(\Phi_{1})]},$$
(2)

where  $I_0$ =4.5  $\mu$ A at 0.3 K is the junction zero field critical current and

$$\delta(\Phi_1) = \pi \frac{\Phi_1}{\Phi_0} + \frac{L_{\text{self}}}{2L_J^0} \sin[\delta(\Phi_1)], \qquad (3)$$

where  $L_{\text{self}} \sim 15$  pH is the self-inductance of the tank circuit SQUID and  $L_J^0 = L_J(\Phi_1 = \Phi_0) = 71$  pH at 0.3 K. In order to have a good sensitivity,  $\delta(\Phi_1)$  has to vary from 0 to almost  $\pi/2$ , which only happens if  $L_{self} \ll L_I^0$  as it is the case here. As expected from Eqs. (2) and (3), the change in the Josephson inductance (and thus also the change of the resonant frequency) is almost zero at  $\Phi_1 = \Phi_0$  and increases strongly when approaching  $\Phi_1 = \Phi_0/2$ . In order to have a good sensitivity as well as a good quality factor Q, we choose to work about  $65m\Phi_0$  away from  $\Phi_1 = \Phi_0/2$ , which corresponds to curves 5 and 6 on Fig. 2. Notice that the decrease of the Qwhen  $\Phi_1$  approaches  $\Phi_0/2$  is probably due to the presence of the superconducting ground plane coupling more noise. Such a ground plane is not necessary if a smaller SQUID having a lower self-inductance is used, as would ideally be the case with real qubits.

Turning "ON" the microstrip amplifier corresponds to applying a dc current bias  $I_{b2}$  and a dc flux  $\Phi_2$  such that the transfer function  $dV_2/d\Phi_2$  and so also the gain are maximized. Both optimums corresponding to the largest positive and negative transfer function (of +600 and -560  $\mu V/\Phi_0$ , respectively) have been considered (see Fig. 3).

As we vary the voltage  $V_{\rm VD}$  across the varactor diode situated at the end of the microstrip, the frequency of the MSA can be tuned. The flux in the tank circuit SQUID  $\Phi_1$  is here equal to  $0.475\Phi_0$  and so the tank frequency when the MSA is "OFF" is about 560 MHz. The same behavior is seen even with  $\Phi_1 = \Phi_0$ . If the positive transfer function is chosen, an anticrossing behavior is observed. Indeed, as the frequency of the MSA is increased in order to bring it closer to that of the tank circuit, repulsion occurs and the peak in the transmission curve initially corresponding to the tank seems to be pushed away. Although the coupling capacitor is small, this behavior is the one expected given the high quality factor of the two resonators in play. An inductive readout was also performed in this anticrossing regime but the best results were obtained when the negative transfer function was chosen. Then, instead of an avoided crossing, the two resonant frequencies allow a complete crossing when they are set on top of each other with even a small attraction between them in this case. Such different behaviors of the MSA according to the sign of its transfer function are related to feedback effects.<sup>10</sup> As shown in Fig. 3, the crossing case permits (see curve  $V_{VD}=13$  V) a gain about 10 dB larger than in the anticrossing case so the best readout performances were obtained in this crossing case with  $V_{VD}=13$  V. To perform a dispersive readout, the input power should be sufficiently



FIG. 3. Transmission vs frequency curves obtained at  $\Phi_1$ =0.475 $\Phi_0$  with a network analyzer at 0.309 K (-99 dBm incoming power) with the MSA ON, i.e., optimally biased to have the largest respectively positive or negative transfer function (upper or lower figure). The voltage  $V_{\rm VD}$  across the varactor diode placed at the end of the microstrip is varied. The calibration was performed with the PC board (as illustrated in Fig. 1) replaced by a short transmission line.

low that the critical current of the tank circuit SQUID is not reached since no energy can be left behind. This is indeed the case if the incoming power is -99 dBm. In this case, the gain of the MSA is about 25 dB (see Fig. 4, compare, e.g., curves 1 and 3).

Curves 3 and 4 illustrate a  $6m\Phi_0$  change applied at the input of the readout device (corresponding to a Josephson inductance change of 13 pH per junction). At the optimum readout frequency of 561 MHz, the sensitivity relative to the output of the MSA is 69  $\mu V/\Phi_0$  and the flux noise relative to the input tank circuit SQUID is  $\Phi_{1N} = 4\mu\Phi_0/\sqrt{\text{Hz}}$ . An even better flux noise of  $\Phi_{1N}=2\mu\Phi_0/\sqrt{Hz}$  was achieved with an incoming power of -90 dBm (and at a frequency of 562 MHz) but in this case, the tank SQUID critical current was exceeded, which is not desirable for measuring a qubit in a dispersive way. The best flux noise obtained with this device at 0.3 K is thus  $\Phi_{1N}=4\mu\Phi_0/\sqrt{Hz}$ , which is very satisfactory. In the real device for reading a qubit, the two tank circuit capacitors would ideally be on-chip, therefore reducing the stray inductors and thus producing an even better flux noise via an increase in the sensitivity. Moreover, going from 0.3 K to 30 mK would also reduce further the noise from the tank circuit as well as the noise from the MSA. Both these im-



FIG. 4. Transmitted power vs frequency measured with a spectrum analyzer for a couple of input flux values ( $6m\Phi_0$  apart) with the MSA OFF or ON with an incoming power of -99 or -90 dBm. Inset: power spectrum at 561 MHz for curves 3 and 4.

provements would allow an even faster measurement of the qubit state or an even stronger decoupling of the qubit from this readout device (via a decrease of the coupling capacitor).

In conclusion, the feasibility of an inductive qubit readout scheme coupled to a MSA has been shown experimentally. Very low flux noise as low as  $4\mu\Phi_0/\sqrt{\text{Hz}}$  was already achieved at 0.3 K with off-chip capacitors for the tank circuit. Even better performances could thus be achieved in the final design were capacitors to be on-chip and the temperature to be an order of magnitude lower. Such a reading device involving the MSA as a first postamplifier is means of avoiding one of the dominant noise sources coming from the HEMT amplifier, the noise temperature of which is typically 2–4 K.

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