PERIODIC RESPONSE OF SUPERCONDUCTING HIGH QUALITY MgB_2 RESONATOR TO MAGNETIC FIELD

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1. Introduction

Coplanar waveguide resonators (CPW) are distributed element electrical resonators which can be easily designed and fabricated by standard photolithographic methods on metalized substrates [1]. Since they are being used with great success in quantum information experiments [2, 3] and in superconducting kinetic inductance detectors for astrophysics [4], they are a subject of intensive research.

In quantum information experiments a superconducting CPW resonator´s photon field is coherently coupled to superconducting qubit. Superconducting qubits are artificially designed nonlinear electrical circuits based on macroscopic quantum phenomena in superconducting Josephson structures. The small transversal dimensions of CPW resonators result in strong confinement of the resonators electromagnetic field allowing strong qubit-resonator coupling. In these experiments, known as circuit quantum electrodynamics experiments, the high internal quality factor of the resonator is substantial to obtain long coherence time of the qubit-resonator system.

Along the standard materials, as for example niobium and aluminum, one possible promising material could be Magnesium diborite (MgB_2). An advantage of this polycrystalline material is the significantly higher critical temperature ~39 K [5], which can be essential for quantum information experiments on hybrid systems at liquid helium temperature [6].

In this paper we present fabrication and characterization of superconducting CPW resonator on 300 nm thick MgB_2 film. We demonstrate high internal quality of the resonator at 300 mK temperature and report a periodic response of transmission of superconducting high quality MgB_2 resonator to magnetic field.

2. MgB_2 layers and resonator fabrication

Superconducting MgB_2 thin film was prepared by co-deposition of Magnesium and Boron from two separate sources on a mirror-polished sapphire substrate and ex-situ annealing in vacuum chamber. The deposition chamber was evacuated to the limit vacuum $5x10^{-4}$ Pa. The resistive thermal evaporation and e-beam evaporation were used to make a precursor of MgB. Ex-situ annealing process was realized in vacuum chamber evacuated to the base pressure of 1.10^{-3} Pa and consecutively filled with Ar up to working pressure of 700Pa. The annealing temperature was 800 ^{o}C.

The resonators were patterned in optical lithography using a *2,5 μm* thick layer of positive tone resist *AZ 6624* and reactively ion etched in *Ar* and SF_6 plasma.

3. Coplanar waveguide resonator design

Coplanar waveguide resonators are based on coplanar wave guides, consisting of a metalized center conductor of width *w* separated from the lateral ground planes by a gap of width s on a substrate with relative dielectric constant ε_r. These parameters define the characteristic impedance of the transmission line for transversal electromagnetic mode wave propagation. If two gaps are isolating a finite length l of the center conductor an effective λ/2 resonator is created. The center conductor is coupled via these gap capacitors to the input and output transmission lines. The coupling strength and the fundamental frequency of the resonator are controlled by the gap capacitors design and the center conductor's length, respectively (Fig. 1).

The center conductor width of our half-wave resonator design is $w=50\ \mu m$, the separation from the ground plane is s =30 μm, corresponding to $50\ \Omega$ impedance. The length of the resonator is l=24 mm, corresponding to fundamental frequency of *2.703* GHz at zero temperature for 300 nm thick superconducting layer deposited on sapphire dielectric layer with $450\ \mu m$ thickness and relative dielectric constant $\varepsilon_r=9.5$. The estimated loaded quality factor for this design is *38 800*, inductance $L=1.88\ nH$, capacitance $C=1.85\ pF$ and coupling capacitances $C_\kappa=5.3$ fF. To design and simulate the properties of our resonator a commercial high frequency electromagnetic software Sonnet [7] was used.

4. Experimental set-up

The transmission of the resonator was measured in a temperature range from 40 K to 0.3 K in cryogen-free He^3 refrigerator [8]. The resonator was glued and wire-bonded to the printed circuit board with 50µm aluminum wires and enclosed in a copper box. The experimental set-up consisted of a set of thermally anchored attenuators and coaxial cables on the input lines and of cryogenic circulator (2.2-3GHz), superconducting niobium coaxial cable and stainless steel cable on the output line (Fig. 1). The output signal was amplified by a room temperature amplifier (B&Z BZP 112UC1 0.1-12Ghz). The transmission of the resonator was measured using an Agilent network analyzer (N5242A). To apply dc magnetic field perpendicular to the resonator a pair of current biased coil of wounded superconducting NbTi wire were attached on each side of the copper box constituting Helmholtz coils. The bias lines of the coils were filtered by a carbon powder filter to reduce the dc magnetic field fluctuations.

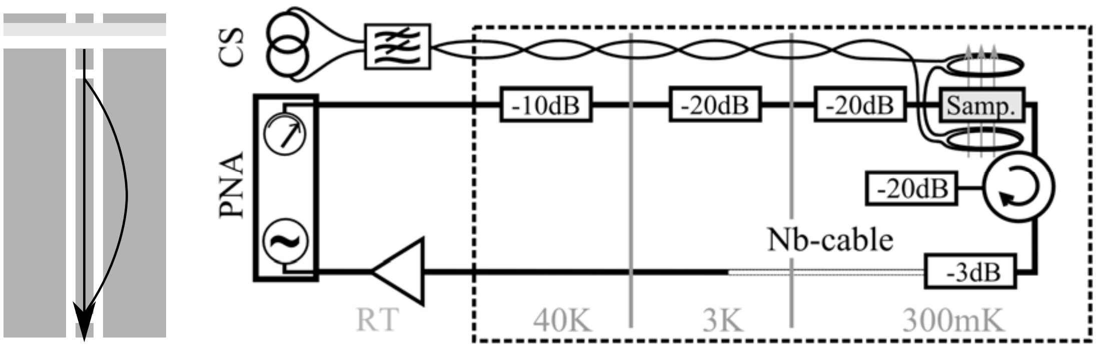

Fig.1: *Scheme of a λ/2 CPW resonators cross section and layout (on the left) and scheme of the rf-experimental set-up (on the left)*

5. **Results**

The central frequency (CF) and quality factor of the resonator were estimated from the Lorentzian fit of the measured transmission spectrum of the resonator. The fundamental resonance frequency and measured loaded quality of the resonator at 300 mK is *2.703 GHz* and *37 500*, respectively. Taking into account the design of the resonator, the estimated internal quality factor of the resonator is found to be *>10⁶*. The temperature dependence of the central frequency and the quality factor was measured and compared with modified Mattis-Bardeen theory [9] taking into account two band structure of MgB_2. The critical temperature $T_c \approx 33$ K of the MgB_2 layer was estimated from the temperature dependence of the central frequency (Fig. 2).

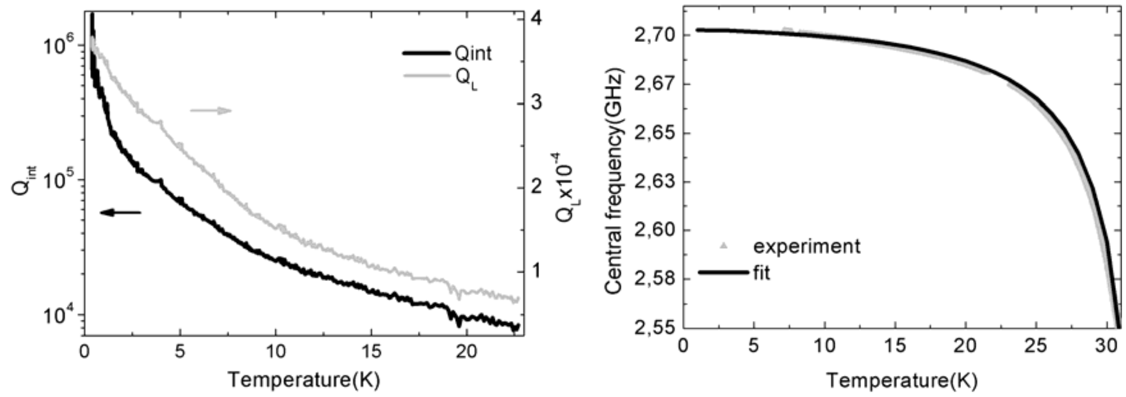

Fig. 2: Left panel: the measured temperature dependence of the loaded quality factor Q_L (solid line) and the estimated internal quality factor Q_{int} (dashed line) of the resonator. Right panel: the measured temperature dependence of the central frequency (triangles) and it's fit using modified Mattis-Bardeen theory (solid line).

Applying perpendicular dc magnetic field to the resonator we studied the dependence of the central frequency, quality and maximal transmission of the resonator. While the quality factor and maximal transmission of the resonator stayed unchanged during a magnetic field sweep, the central frequency of the resonator showed a periodic dispersive shift (Fig. 3). This change in the resonant frequency reveals a magnetic field dependency of the effective inductance of the resonator. This effect is well known for rf SQUID – a single Josephson junction closed to superconducting loop with inductance *L* and inductively coupled to the resonator.

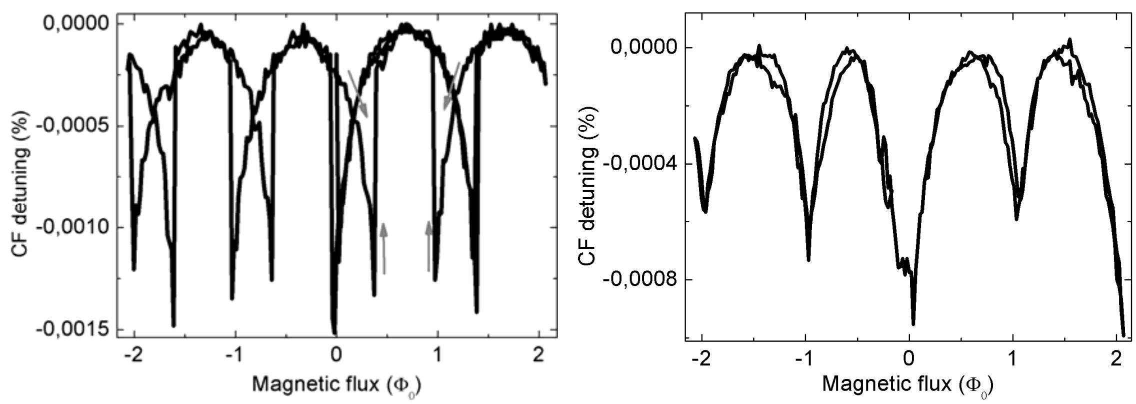

Fig. 3: The detuning of the resonator central frequency from the maximum central frequency as a function of the applied dc magnetic field at temperature 3.5 K *(left panel) and at 11 K (right panel). The magnetic field was normalized to magnetic flux quantum $\Phi_0=h/2e$, here h is the Planck's constant. The jumps, marked by arrows, clearly demonstrate a hysteretic rf SQUID-like behavior. For temperatures above 11* K *the rf SQUID-like behavior is becoming nonhysteretic.*

As the temperature of SQUID is decreasing, the critical current I_c of the junction is increasing. If parameter $\beta_L=2\pi LI_c/\Phi_0$ [10], characterizing the junction, exceeds the critical value of 1 the rf-SQUID becomes hysteretic. Indeed, by measuring the magnetic field dependency of the resonators central frequency at different temperatures we found a non-hysteretic to hysteretic transition at ≈11 K. Since there was no artificially prepared rf SQUID the periodic behavior should originate from response of superconducting loops formatted among grains. Similar feature has been already observed in bulk samples of polycrystalline MgB_2 [12] where a low quality copper coil was used a pick-up tank. Radio frequency-SQUID effect due to natural grain boundary weak links has been also observed on YNi_2B_2C [13].

6. Conclusion

We prepared and characterized an MgB_2 CPW resonator in the temperature range from 40 K to 0.3 K. The internal quality factor of our resonator is $>10^6$, which is comparable to the most commonly used niobium layer resonators in similar geometry for circuit quantum electrodynamics experiments [11]. Moreover, we demonstrated a periodic response of the MgB_2 resonator to magnetic field. A possible explanation of this behavior can be a natural creation of weak links on the grain boundaries of polycrystalline MgB_2. Additional measurements on a set of resonators are required, in order to prove the repeability of this rf-SQUID behavior and study this nontrivial behavior as a complex function of processing conditions and resonator design. This work is in progress.

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