Protecting SQUID metamaterials against stray magnetic fields

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Abstract
Using superconducting quantum interference devices (SQUIDs) as the basic, low-loss
elements of thin-film metamaterials has one main advantage: their resonance frequency is
easily tunable by applying a weak magnetic field. The downside, however, is a strong
sensitivity to stray and inhomogeneous magnetic fields. In this work, we demonstrate that even
small magnetic fields from electronic components destroy the collective, resonant behaviour
of the SQUID metamaterial. We also show how the effect of these fields can be minimized. As
a first step, magnetic shielding decreases any initially present fields, including the earth's
magnetic field. However, further measures such as improvements in the sample geometry have
to be taken to avoid the trapping of Abrikosov vortices.

(Some figures may appear in colour only in the online journal)

1. Introduction

The research field of superconducting metamaterials that
employ the nonlinear inductance of a Josephson junction
as a tunable element is just emerging. Unlike other
superconducting metamaterials [1, 2], the tuning of the
so-called Josephson inductance does not degrade the quality
factor of the resonance over almost the full range of tunability.
The idea of a metamaterial consisting of superconducting
quantum interference devices (SQUIDs) was theoretically
introduced and investigated in [3–5]. Recently, the single
junction (rf-) SQUID as a meta-atom tunable by a magnetic
field has been experimentally investigated in [6] and employed
successfully as a basic building block of a metamaterial in [7].
However, the easily accessible, broad range tunability comes
at the cost of a high sensitivity to external magnetic fields.

Here, we demonstrate and discuss measures that are
necessary to use rf-SQUIDs as the building blocks of a
superconducting metamaterial. In order to generate a coherent
response, all SQUIDs have to have the same resonance
frequency at the same magnetic field, i.e. the resonance curves
of the individual SQUIDs have to overlap.

Stray magnetic fields are caused either by the magnetic
components used in the experimental setup or outside sources
such as the earth's magnetic field. They have two main

effects that disturb the collective behaviour. First, a spatially
inhomogeneous field is created at the sample. This means
that each SQUID is biased with a different magnetic field.
Second, if there is a magnetic field present when cooling the
sample from above to below the critical temperature of the
superconductor, Abrikosov vortices [8] can be trapped in the
thin Nb film. The vortices create local magnetic fields that
remain in the superconductor until the sample is warmed up
again.

Thus, any stray magnetic field has to be screened as well
as possible and, additionally, the sample has to be designed
in such a way as to discourage the trapping of Abrikosov
vortices. The latter can be done by using normal metal
instead of superconductors where possible and by decreasing
the width of the superconducting structures in order to
reduce their demagnetization factor [9, 10]. Additionally,
these vortices are trapped preferably at inhomogeneities in the
superconductor [10], for example at vias where two layers of
superconductor connect. Thus, the area of these vias should
be chosen to be as small as possible.

2. The SQUID metamaterial

We performed experiments with a one-dimensional metama-
terial that contains rf-SQUIDs as meta-atoms. A chain of these
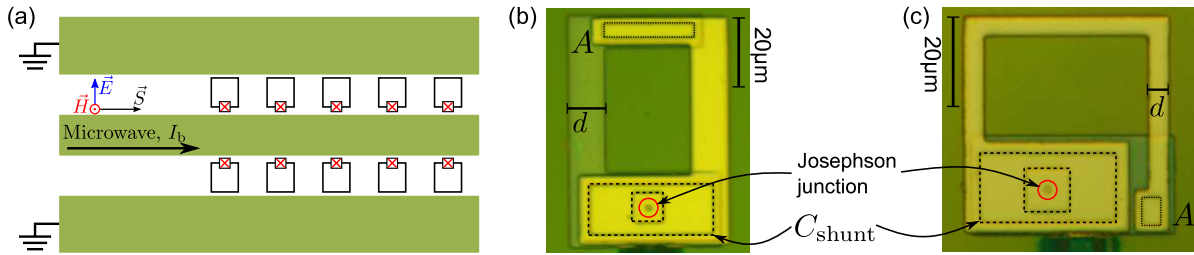
Figure 1. (a) Coplanar waveguide geometry including the rf-SQUIDs. The vectors $\vec{E}$, $\vec{H}$ and $\vec{S}$ denote the direction of electric field, magnetic field and Poynting vector, respectively. (b) Single rf-SQUID used in sample S1 including junction, shunt capacitance C_{shunt}, via area A and line width d as mentioned in the text. (c) Single rf-SQUID used in sample S2, note the different line width $d_{\text{S1}} = 10\ \mu$m versus $d_{\text{S2}} = 4\ \mu$m and via area $A_{\text{S1}} = 25 \times 3\ \mu$m^2 versus $A_{\text{S2}} = 5 \times 3\ \mu$m^2.

Table 1. SQUID parameters for the two different samples S1 and S2 used in the measurements described in section 4.

	I_c (μA)	$L_j(\Phi_{e0} = 0)$ (pH)	L_{geo} (pH)	β_L	C_{tot} (pF)
S1	3.4	97	78	0.80	1.5
S2	1.8	183	83	0.45	2.0

rf-SQUIDs is placed inside each gap of a coplanar waveguide (CPW) (see figure 1(a)). The SQUIDs as well as the CPW are fabricated on a Si substrate using a Nb/AlO$_x$/Nb trilayer process. A small amplitude microwave signal travels along the waveguide. In addition, the central conductor is used to bias the rf-SQUIDs with a dc magnetic field by applying a dc current I_b. Note that in the presentation of the measured data in section 4, instead of magnetic field we use the more natural quantity magnetic flux per SQUID loop.

In this work, we consider two different samples, each containing 54 SQUIDs, 27 per gap. Sample S1 contains a fully superconducting waveguide made of Nb. One of the SQUIDs, used in sample S1, is shown in figure 1(b). Its parameters, namely the critical current of the Josephson junction I_c, the resulting zero-field Josephson inductance L_j, as well as the geometric inductance of the SQUID loop, are given in table 1.

The rf-SQUID of the second sample S2 is shown in figure 1(c). Its parameters are different from those of the SQUIDs of sample S1. They are also given in table 1. Both SQUIDs have a $\beta_L = 2\pi L_{\text{geo}} I_c / \Phi_0 < 1$ and use a parallel plate capacitor C_{shunt} that shunts the junction to increase the total capacitance C_{tot} of the circuit, thus decreasing the resonance frequency.

Due to the different design, the occurrence of Abrikosov vortices should be considerably suppressed in sample S2. For example, the SQUIDs used in S2 have a smaller width d of the superconducting leads and area of the via A. Additionally, the ground planes of the CPW of sample S2 are made of normal metal (Pd) instead of Nb. The central conductor is still made from Nb, due to requirements of the fabrication process.

3. Measurement setup

The 4 mm × 4 mm Si chip that holds the CPW with the SQUIDs is glued to a printed circuit board that is used to connect the coaxial cables to the CPW. This setup is then installed inside a cylindrical copper sample holder.
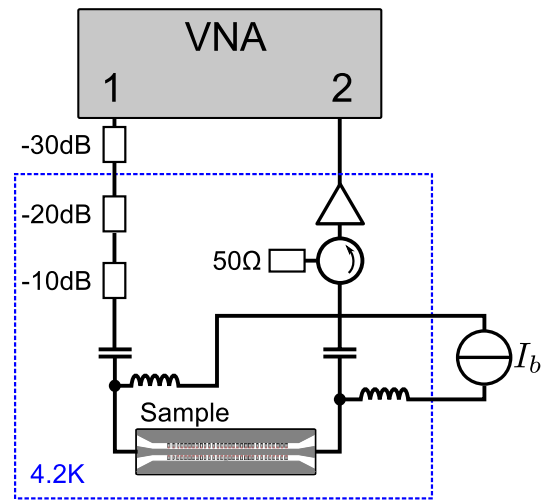
Figure 2. Measurement setup including the vector network analyzer (VNA), bias tees, attenuation, circulator and cryogenic amplifier.

The sample holder, including the microwave electronics, i.e. attenuators, circulator, amplifier and bias tees, is placed inside a cylindrical Cryoperm shield to suppress external magnetic fields. The bias tees are used to superpose the microwave signal with the dc current used to tune the resonance frequency of the rf-SQUIDs.

The setup is then installed on a dip stick and immersed in liquid helium. The microwave lines are connected to a vector network analyzer (VNA) using additional warm attenuation at the input. The full setup, apart from the Cryoperm shield, is shown in figure 2.

We measure the field- and frequency-dependent complex transmission S_{21} through the sample.

4. Experimental results

Here, we present experimental results obtained with different setups and different samples S1 and S2. First, we consider a measurement performed on sample S1. For better visibility, all measurements except the one shown in figure 5 are normalized for each frequency value with the average transmission magnitude along the flux axis. The resulting transmission data is presented with colour coding in figure 3.
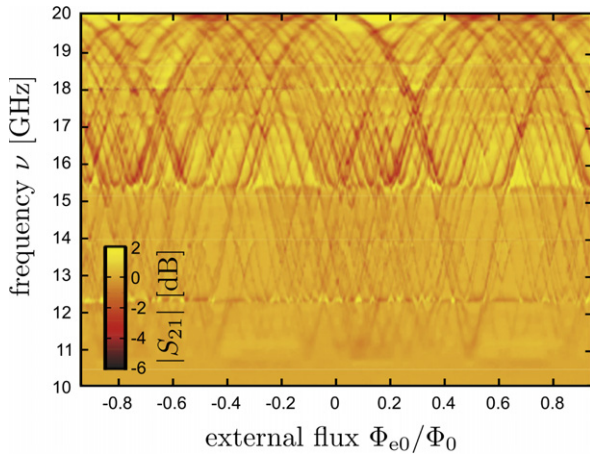
Figure 3. Flux- and frequency-dependent transmission magnitude measured on sample S1. The measured data is normalized along the flux axis in order to improve visibility of the lines.

The picture shows many lines spread randomly over the full flux range.

Every line corresponds to the magnetic field dependent resonance curve of one or a small number of rf-SQUIDs and each of these individual or small groups of SQUIDs is thus biased with different magnetic field. The lines at approximately 11, 12.2 and 15.5 GHz are internal parasitical sample holder resonances that couple to the SQUIDs and distort the resonance lines. When looking more closely, one notices that different individual lines seem to have a slightly different periodicity in magnetic flux as well as a slightly different frequency range. This is an effect of a small spread in SQUID parameters.

In order to decrease the spread in magnetic flux bias, sample S1 was replaced by sample S2, which is built to reduce the trapping of Abrikosov vortices. However, the resulting transmission again shows the same forest of lines (not shown here). Thus, further measures to improve the setup had to be taken.

First, all components were examined to determine if and how strongly they are magnetic. The strongest magnetic field is created by the circulator. Since we used it only as protection from reflections from the amplifier back to the sample, we replaced it by a 3 dB attenuator which serves the same purpose. The amplifier and the bias tees are also magnetic. They, however, are essential to our measurement setup. In order to protect the sample from their fields, they a placed outside the Cryoperm shield. In figure 4(a), it is clearly visible that these measures improved the behaviour of our SQUID metamaterial significantly. The spread of the lines is strongly reduced. Note that due to the different SQUIDs parameters, the frequency band in which the resonance frequency is tunable is changed according to the values given for S2 in table 1. However, the microwave cables are also magnetic. This creates another complication. They have to connect to the sample and cannot be removed or installed far away. Thus, care has to be taken that they do not pass closely by the sample. The cables that are used close to the sample contain a
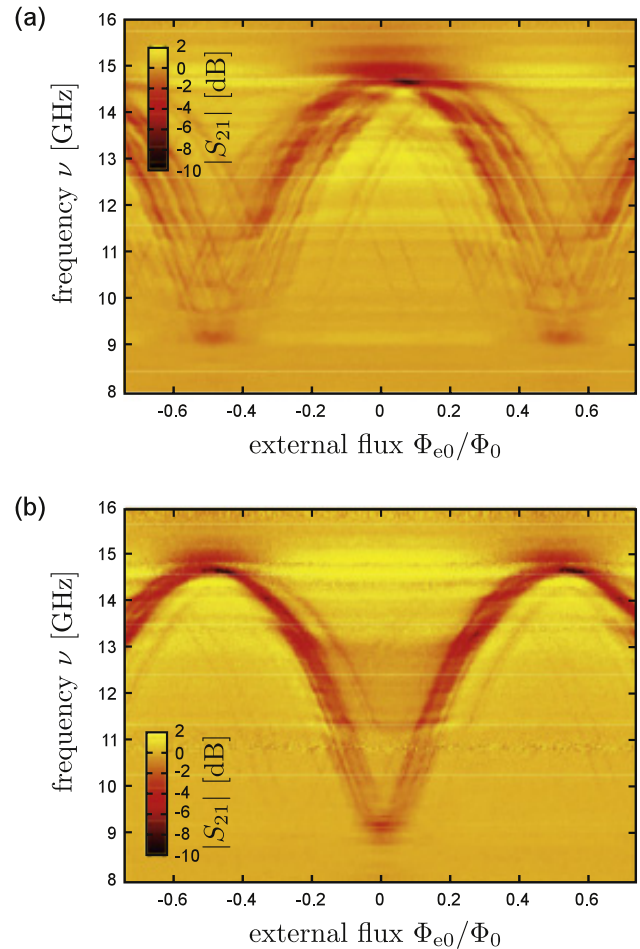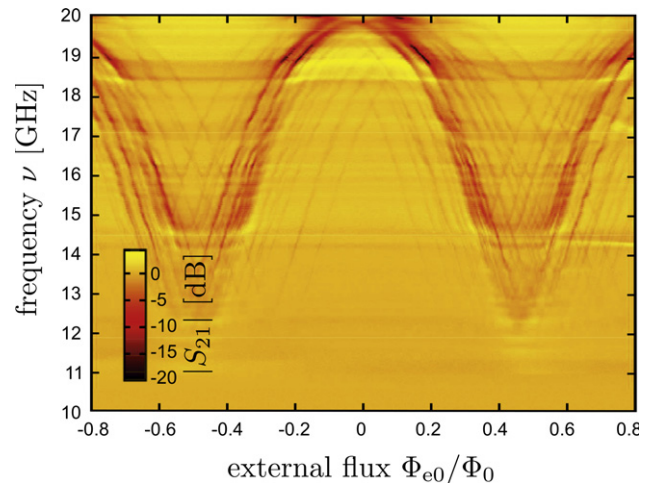

Figure 4. Transmission magnitude through sample S2. (a) All necessary microwave electronics, such as the amplifier and the bias tees, are installed outside the magnetic shield. However, a microwave cable is close to the top of the sample and the sample is placed in the upper third of the shield. (b) Sample is moved deep into the shield (lower third) and the microwave cable passes at the side of the sample.

central conductor made of copper and silver-plated steel and an outer conductor made of tin-plated copper. Figures 4(a), (b) and 5 show how the magnetic environment is considerably improved by careful arrangement of the cables. In figure 4(a) one cable passes on top of the sample holder with a distance of approximately 10 mm to the sample. In (b) this cable is moved to pass along the side of the sample and the sample is moved as far into the cylindrical Cryoperm shield as possible. In figure 5, a different sample holder at the same position deep inside the Cryoperm shield is used, which allows the microwave cables to be led away from the sample without passing it. Finally, with this improved setup, a main resonance is clearly visible. Figures 4 and 5 show that protecting the sample from magnetic fields is crucial as even the stray fields of microwave cables affect the outcome. It should be emphasized that this result was obtained with sample S2.

We now change back to sample design S1. When we install it in exactly the same setup as the one used for the measurement on sample S2 in figure 5, the quality of the
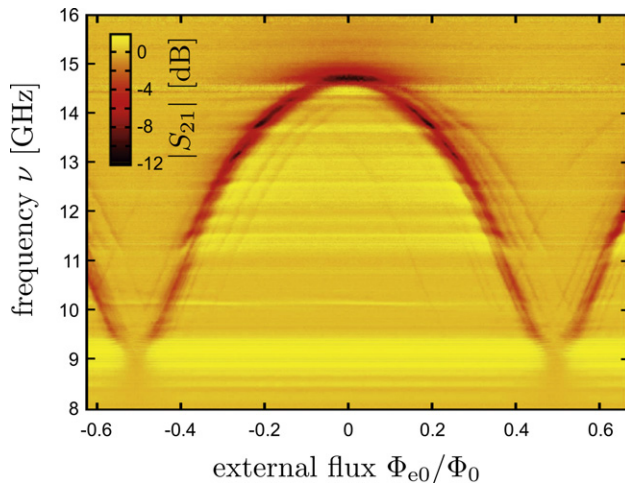
Figure 5. Transmission magnitude through sample S2 when the microwave cable does not pass the sample. Note the calibration for this measurement was done *in situ*, using the through calibration function of the VNA at an external flux $\Phi_{e0} = 0.5\Phi_0$.

Figure 6. Transmission magnitude through sample S1 with the same setup used in the measurement shown in figure 5.

result is degraded again (see figure 6). The deviation in critical current as well as capacitance is less than 6% for both samples. However, as mentioned above, there is also some spread in the periodicity in magnetic flux. This is due to slightly different areas of the individual SQUIDs, since the magnetic bias is applied along the central conductor and should be homogeneous. For sample S1, the spread is up to 12%, while it is less (about 2%) for sample S2. This deviation contributes to the degradation, since the resonance curves of deviating SQUIDs are shifted by up to $0.1\Phi_0$ against the standard curves in the flux interval shown in figure 6. However, this deviation is neither strong enough to explain the full spread in magnetic flux nor does it affect all resonance curves. Instead, the main difference between the two samples S1 and S2 is their affinity to trap Abrikosov vortices. Thus, the vortices are most probably the reason for the degradation of the performance of sample S1 under otherwise identical measurement conditions as for sample S2.

5. Conclusion

On the road towards creating a tunable magnetic metamaterial with a collective resonance frequency, we had to solve a few challenges by overcoming the effects of stray magnetic fields. We have shown that the inhomogeneous magnetic flux bias of the individual SQUIDs arises from fields due to magnetic components of the measurement setup as well as trapped Abrikosov vortices in the superconducting film. Apart from shielding the sample magnetically, two main measures have to be taken to protect against both effects. First, magnetic components that cannot be omitted have to be placed as far away from the sample as possible. Care has to be taken even with coaxial cables. Second, the trapping of Abrikosov vortices has to be prevented by using superconducting planes only where necessary and by decreasing the width of the superconducting leads of the SQUID and the area of the via

which creates the contact between different superconducting layers. Applying all these measures, we were able to achieve a collective, tunable resonance curve of almost all 54 rf-SQUIDs.

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