Protecting SQUID metamaterials against stray magnetic fields

S Butz1, P Jung1, L V Filippenko2,3, V P Koshelets2,3 and A V Ustinov1,3

1 Physikalisches Institut, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany
2 Kotel’nikov Institute of Radio Engineering and Electronics (IREE RAS), Moscow 125009, Russia
3 National University of Science and Technology MISIS, Moscow 119049, Russia

E-mail: s.butz@kit.edu

Received 30 April 2013, in final form 19 June 2013
Published 29 July 2013
Online at stacks.iop.org/SUST/26/094003

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.

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 metamaterial that contains rf-SQUIDs as meta-atoms. A chain of these
Figure 1. (a) Coplanar waveguide geometry including the rf-SQUIDs. The vectors $\mathbf{E}$, $\mathbf{H}$ and $\mathbf{S}$ denote the direction of electric field, magnetic field and Poynting vector, respectively. (b) Single rf-SQUID used in sample S1 including junction, shunt capacitance $C_{\text{shunt}}$, 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 $d_{S1} = 10 \, \mu m$ versus $d_{S2} = 4 \, \mu m$ and via area $A_{S1} = 25 \times 3 \, \mu m^2$ versus $A_{S2} = 5 \times 3 \, \mu m^2$.

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

|      | $I_c$ (µA) | $L_j(\Phi_0 = 0)$ (pH) | $L_{\text{geo}}$ (pH) | $\beta_L$ | $C_{\text{tot}}$ (pF) |
|------|------------|-------------------------|------------------------|-----------|----------------------|
| S1   | 3.4        | 97                      | 78                     | 0.80      | 1.5                  |
| S2   | 1.8        | 183                     | 83                     | 0.45      | 2.0                  |

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. However, they are essential to our measurement setup. In order to protect the sample from their fields, they are placed outside the magnetic 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 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...
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 0.1φ0 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.

Acknowledgments

The authors would like to acknowledge interesting and productive discussions with S M Anlage, I Gabitov, N Lazarides and G Tsironis. This work was supported in part by the Ministry of Education and Science of the Russian Federation, by the Russian Foundation of Basic Research, and also by the Deutsche Forschungsgemeinschaft (DFG) and the State of Baden-Württemberg through the DFG Center for Functional Nanostructures (CFN). Philipp Jung would like to acknowledge the financial support by the Helmholtz International Research School for Teratronics (HIRST), Susanne Butz would like to acknowledge the financial support by the Landesgraduiertenförderung Baden-Württemberg.

References

[1] Ricci M C, Xu H, Prozorov R, Zhuravel A P, Ustinov A V and Anlage S M 2007 IEEE Trans. Appl. Supercond. 17 918
[2] Gu J, Singh R, Tian Z, Cao W, Xing Q, He M, Zhang J W, Han J, Chen H and Zhang W 2010 Appl. Phys. Lett. 97 071102
[3] Lazarides N and Tsironis G P 2007 Appl. Phys. Lett. 90 163501
[4] Maimistov A I and Gabitov I R 2010 Opt. Commun. 283 1633
[5] Du C, Chen H and Li S 2008 J. Phys.: Condens. Matter 20 345220
[6] Jung P, Butz S, Shitov S V and Ustinov A V 2013 Appl. Phys. Lett. 102 062601
[7] Butz S, Jung P, Filippenko L V, Koshelets V P and Ustinov A V 2013 Opt. Express to be published
[8] Abrikosov A A 1957 Sov. Phys.—JETP 5 1174 (Engl. transl.)
[9] Stan G, Field S B and Martinis J M 2004 Phys. Rev. Lett. 92 097003
[10] Polyakov Y, Narayana S and Semenov V K 2007 IEEE Trans. Appl. Supercond. 17 520