Investigation of Helium-Cooled Planar Transformer-Coupled SQUID Magnetometer

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Abstract. We investigated helium-cooled planar transformer-coupled SQUID magnetometers with regard to their field resolution $\delta B$ by varying the SQUID loop inductance $L_s$, input coils and the pick-up loop $L_p$. It was found that the pick-up loop area $A_p$ is the most important parameter for $\delta B$ of transformer-coupled magnetometers. $\delta B$ with $A_p = 10 \times 10 \text{mm}^2$ reached about 3 fT/$\sqrt{\text{Hz}}$, even using direct readout scheme without any feedback circuitries.

1. Introduction

Our transformer-coupled SQUID magnetometer consists of three parts: a dual-washer SQUID with two series-opposite integrated input coils $L_{in}$ connected to an on-chip pickup loop $L_p$.

An important figure of merit for a magnetometer is the magnetic field resolution $\delta B$, which is a product of the SQUID system flux noise $\delta \Phi$ and the flux-to-field transfer coefficient $\partial B/\partial \Phi$, i.e., $\delta B = \delta \Phi \times (\partial B/\partial \Phi)$. $\delta \Phi$ consists of two parts, the SQUID intrinsic noise $\delta \Phi_i$ and the preamplifier noise contribution $\delta \Phi_{\text{preamp}}$, i.e., $\delta \Phi^2 = \delta \Phi_i^2 + \delta \Phi_{\text{preamp}}^2$. Minimizing $\delta \Phi$ of SQUIDs was analyzed in detail in many previous studies, e.g., in reference [1]. For transformer-coupled magnetometers, $\partial B/\partial \Phi$ can be represented as $\partial B/\partial \Phi = (L_p/\sqrt{L_{in,eff}} + \sqrt{L_{in,eff}})/(kL_{s,eff} \times A_{p,eff})$ [2], whereby $L_p$ and $A_{p,eff}$ denote the inductance and the effective area of the pick-up loop, $L_{in,eff}$ and $L_{s,eff}$ the effective inductances of...
the input coil and the SQUID loop, and $k$ the corresponding coupling coefficient. The value of $L_{in,\text{eff}}$ should be designed to equal $L_p$ in order to achieve a minimum of $\partial B/\partial \Phi$ for a given $L_{s,\text{eff}}$. Generally, larger $L_s$ leads to a larger $\delta \Phi$, but a smaller (i.e., better) value of $\partial B/\partial \Phi$. In practice, most magnetometers are designed with $L_s > 100$ pH to meet the high field resolution requirements [3].

We experimentally studied the properties of magnetometers employing SQUIDs with large $\beta_c \approx 3$ to find the combination of inductances $L_s, L_{in}$ and $L_p$ that is optimum for minimizing $\delta B$.

2. Experiments and results

2.1. SQUID magnetometer and readout electronics

In our experiments, mostly SQUID magnetometers with Steward-McCumber parameter $\beta_c \approx 3$ were employed. In our earlier work we have shown that large $\beta_c$ leads to a large flux-to-voltage transfer coefficient $\partial V/\partial \Phi > 300$ µV/Φ₀ at $L_s = 350$ pH [4], thus reducing $\delta \Phi_{\text{preamp}} = V_n/(\partial V/\partial \Phi)$, whereby the preamplifier voltage noise $V_n$ is 0.9 nV/√Hz (AD797). In this case, the SQUIDs can be connected to the preamplifier directly without any feedback circuitries in order to construct a simple SQUID system with an acceptable $\delta \Phi$ [5], measured in flux-locked loop (FLL) inside a niobium shielding tube. The general layout of our SQUID magnetometer is shown in reference [6]. In this layout, we used the dual-washer gradiometric SQUID to increase the coupling between $L_s$ and $L_{in}$.

2.2. Different input coil types

We designed and fabricated three types of input coils, with the input coil consisting of $4.5 \times 2$ turns (see figure 1(a)) at $L_s = 350$ pH and $A_p = 5 \times 5$ mm²: (i) whole coil placed on the SQUID washer of “Ketchen-type” [7]; (ii) whole coil located inside the hole of the SQUID washer; (iii) a part of coil is overlaying the SQUID washer and the other part is inside the hole. Subsequently, we measured $\delta \Phi$ and $\partial B/\partial \Phi$ to determine $\delta B$. We found that $\delta \Phi \approx 5$ µΦ₀/√Hz for all types of magnetometers investigated, while $\partial B/\partial \Phi$ strongly depended on the positions of the input coils. The transfer function $\partial B/\partial \Phi$ increased from 1.5 (for type (i)), and 1.6 (for type (iii)) to 2.7 nT/Φ₀ (for type (ii)). Of course, the “Ketchen-type” magnetometer provides the best coupling method for the transformer-coupled SQUID magnetometer. However, it is surprising that placing all of the coil turns inside the SQUID hole (in the case of type (ii)) reduced the effective area of the magnetometer only to about 50 %, because a much smaller value of the effective area was speculated. In the work described below, only input coils of “Ketchen-type” were utilized.

2.3. SQUID effective inductance

In a transformer-coupled magnetometer, the design (geometrical) value of the SQUID inductance $L_s$ is reduced due to the screening effect when the input coils are connected to the pick-up loop. Therefore, we introduce the SQUID effective inductance $L_{s,\text{eff}}$, because it (and not the geometrical inductance $L_s$) is responsible for $\delta B$ of magnetometers. The value of $L_{s,\text{eff}}$ can be determined by the SQUID screening parameter $\beta_c = 2I_c L_{s,\text{eff}}/\Phi_0$, where $I_c$ is the critical current of one junction and $\Phi_0$ is the flux quantum. The value of $\beta_c$ is determined by the ratio of $I_{c,\text{min}}/I_{c,\text{max}}$. The value of $I_{c,\text{max}}$ is $2I_0$ in the above expression of $\beta_c$, when two junctions are identical. The dependence of $\beta_c$ on $I_{c,\text{min}}/I_{c,\text{max}}$ shown in the inset in figure 1(b) is reproduced from [1]. The screening parameter $\beta_c$ increases monotonously with increasing
Figure 1. (a) Schematic layout of dual-washer SQUID and input coils (i) fully overlaying the SQUID washer (“Ketchen-type”), (ii) fully inside the SQUID holes, and (iii) partly overlaying the washer and holes. (b) Measured $I - V$ characteristics of the SQUID magnetometer with $L_s = 350$ pH and $L_{in}$ of $4.5 \times 2$ turns of type (i) in (a). $I_{c_{\text{max}}}$ and $I_{c_{\text{min}}}$ denote the critical currents at integer and half integer flux quantum, and $\Phi_a$ is the applied flux. The inset shows the dependence of the screening parameter $\beta_L$ on $I_{c_{\text{min}}}/I_{c_{\text{max}}}$ from [1].

$I_{c_{\text{min}}}/I_{c_{\text{max}}}$. Its $\beta_L = 0.75$ is obtained from the curve of $\beta_L$ vs. $(I_{c_{\text{min}}}/I_{c_{\text{max}}})$ and the measured $I_{c_{\text{min}}}/I_{c_{\text{max}}} = 0.44 (3.65 \mu A/8.3 \mu A)$, leading to $L_{s,\text{eff}} \approx 181$ pH, almost half of $L_s$ [2].

2.4. Field resolution $\delta B$

To investigate $\delta B$ of the magnetometer, we varied the SQUID layout parameter, such as $L_s$, or the turn number of the input coil. Two SQUID pick-up areas of $A_p = 5 \times 5$ mm$^2$ (table 1) and $10 \times 10$ mm$^2$ (table 2) were employed.

In table 1, three important parameters of the magnetometers, $L_{s,\text{eff}}$, $\delta \Phi$ and $\partial B/\partial \Phi$, are listed. The value of $L_{s,\text{eff}}$, for example, at $L_s = 350$ pH, obviously increases with decreasing the turn number of $L_{in}$, thus increasing $\delta \Phi$, but concurrently improving $\partial B/\partial \Phi$. In fact, for a given $L_s$ of 350pH, $L_{in,\text{eff}}$ slightly changes with the turns of $L_{in}$ varying in a certain range shown in table I and II, since $L_{in,\text{eff}}$ depends on both the turns of $L_{in}$ and $L_{s,\text{eff}}$ [2], which leads to $L_{in,\text{eff}} \approx 14$ nH to match $L_T \approx 15$nH [6]. Consequently, $\delta B$ was almost constant for such transformer-coupled magnetometers, even when varying $L_s$ from 350 up to 620 pH.

| $L_s$ [pH] | 350 | 350 | 350 | 480 | 480 | 620 | 620 |
|------------|-----|-----|-----|-----|-----|-----|-----|
| Turns of $L_{in}$ — | $3.5 \times 2$ | $4.5 \times 2$ | $5.5 \times 2$ | $2.5 \times 2$ | $5.5 \times 2$ | $2.5 \times 2$ | $4.5 \times 2$ |
| $L_{s,\text{eff}}$ [pH] | 235 | 180 | 140 | 365 | 190 | 420 | 310 |
| $\partial B/\partial \Phi$ [nT/Φ0] | 1.47 | 1.50 | 1.63 | 1.24 | 1.53 | 1.09 | 1.28 |
| $\delta \Phi$ [μΦ0/√Hz] | 5.4 | 5 | 4.5 | 6.6 | 5.2 | 7.4 | 5.6 |
| $\delta B$ [fT/√Hz] | 7.9 | 7.5 | 7.3 | 8.2 | 7.9 | 8.1 | 7.2 |
For $A_p$ of $10 \times 10 \text{ mm}^2$ (table 2), we increased the turn number of $L_{in}$, e.g., to $7.5 \times 2$ at $L_s = 350 \text{ pH}$, thereby leading to the reduction of $\frac{\partial B}{\partial \Phi} \approx 0.55 \text{ nT/\Phi}_0$, although $L_{s,\text{eff}}$ further reduced to 120 pH. Indeed, making $A_p$ larger is very useful for the improvement of $\delta B$. For different $L_s$, $\delta B \approx 3 \text{ fT/\sqrt{Hz}}$ of such magnetometers was achieved. Note that $\delta \Phi$ of the present SQUID magnetometers in table 2 was larger than that listed in table 1, due to $\beta_c > 3$. Larger $\beta_c$ led to a higher $\delta \Phi$, which dominated $\delta \Phi$ [5].

Table 2. Parameters of SQUID magnetometers with $A_p$ of $10 \times 10 \text{ mm}^2$

| $L_s$ [pH] | 350  | 480  | 620  |
|-----------|------|------|------|
| Turns of $L_{in}$ | —    | $7.5 \times 2$ | $6.5 \times 2$ | $5.5 \times 2$ |
| $L_{s,\text{eff}}$ [pH] | —    | 120  | 192  | 265  |
| $\frac{\partial B}{\partial \Phi}$ [nT/\Phi_0] | 0.55 | 0.47 | 0.4  |
| $\delta \Phi$ [\mu\Phi_0/\sqrt{Hz}] | 5.5  | 7    | 9.5  |
| $\delta B$ [fT/\sqrt{Hz}] | 3    | 3.3  | 3.8  |

3. Conclusion

We studied different layouts of transformer-coupled SQUID magnetometers with varying $L_s, L_{in}$ and $L_p$. An input coil fully overlaying the SQUID washer ("Ketchen type") provides the best coupling between $L_s$ and $L_{in}$, whereas placing the input coil fully inside the SQUID hole will reduce the pick-up area by about 50%. The effective SQUID inductance $L_{s,\text{eff}}$ obviously increases with decreasing turn number of $L_{in}$, thus increasing $\delta \Phi$, but at the same time reducing $\frac{\partial B}{\partial \Phi}$. Consequently, $\delta B$ is almost constant for a certain pick-up-loop area $A_p$. In other words, $L_s, L_{in}$ and the matching between $L_{in}$ and $L_p$ will not influence greatly $\delta B$. Only by increasing $A_p$ will the field resolution improve.

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