Combined Magnetic Field Sensor with Nanostructured Elements

L P Ichkitidze¹,², S V Selishchev² and D V Telyshev¹,²

¹ National Research University of Electronic Technology, Zelenograd, Moscow, 124498 RF
² I.M.Sechenov First Moscow State Medical University, Moscow, 119435 RF

E-mail: ichkitidze@bms.zone, leo852@inbox.ru

Abstract. A combined magnetic field sensor consisting of a magnetic field concentrator based on a superconducting ring film and a magnetically sensitive element with a spintronics structure is investigated. The active strip (narrowed part) of the concentrator is separated by an insulating film from the magnetically sensitive element, i.e. the combined magnetic field sensor is a sandwich. It has been established that the concentration coefficient of a sandwich-type magnetic field can be increased by fragmentation (nanostructuring) of the active band, in the form of several superconducting branches and cuts 20 nm wide. Increasing the number of incisions also reduces the threshold sensitivity of the sensor by several times. Nanostructured elements in the form of nanoscale sections in the active strip allow you to reduce the diameter of the concentrator ring, which allows the sensor to make the maximum linear size less than 1mm. It is noted that the considered combined magnetic field sensor with nanostructured elements has a high potential for detecting ultraweak magnetic fields (∼ 10 pT), and apparently, can be an alternative to SQUID.

1. Introduction

In many areas of human activity, for example, in electronic compasses, archaeological research, spacecraft, as well as in biomedical applications, magnetic field sensors (MFS) with ultra-low threshold sensitivity of \( \delta B \lesssim 10 \) pT are used [1]. For example, such ultra-weak fields are required to be registered in some archaeological [2,3] and space navigation [4], in magnetic imaging systems, microscopy and metrology [5,6], as well as in biomedical diagnostics [7,8]. The biomagnetic fields generated by the organs of the human body mainly lie in the range of 1 nT - 1 fT, and a large proportion of the use of MFS ultralow \( \delta B \) is in biomedicine. In this area, in some cases, the first type of MFS that does not require cooling may work, in particular, laser-pumped magnetometers [9, 10], flux-gate transducers [11,12], Hall effect sensors [13], and spintronics [1,14,15]. Virtually all of the above listed MFS, having room temperatures as working, do not have sufficiently low threshold sensitivity values (in particular, \( \delta B \geq 10 \) pT), intrinsic noise, and overall dimensions. Therefore, their use in non-invasive biomedical diagnostics is still very uncertain.
MFS of the second type, with cryogenic cooling, have significantly better performance than sensors of the first type. For example, these include: a magnetic modulation magnetometer (MMM) with a core based on a ceramic high-temperature superconducting (HTSC) material [16], a combined MFS (CMFS) [17-19], a superconducting quantum interference sensor (SQUID) [1,20,21]. Of these sensors, only SQUID have a commercial offer [22]. For SQUIDs created on the basis of various materials, the following are implemented: HTSC systems Y-Ba-Cu-O, working temperature $T_w \sim 77$ K, $\delta \Phi \sim 10^{-12}$-10$^{-13}$ T, $\delta B \sim 10^{-5}-10^6 \phi_0$; low-temperature superconducting (LTSC) material Nb, $T_w \sim 4$ K, $\delta B \sim 10^{-15}$ T, $\delta \Phi \sim 10^{-6}-10^{-7} \phi_0$. Here is the threshold sensitivity, $\phi_0 \leq 2.07 \times 10^{-15}$ T·m$^2$ is a quantum of magnetic flux. The principle of operation of the MMM is similar to a flux-gate sensor, but as a magnetically sensitive element (MSE) it has rods of ceramic HTSC materials in the form of a “Josephson medium”. At $T_w \sim 77$ K, they are characterized by acceptable absolute magnetosensitivity ($\geq 10^5$ V/T) [16], values $\delta B \geq 10^{-13}$ T and $\delta \Phi \geq 10^2 \phi_0$, but inferior to SQUIDs. However, they are much cheaper than SQUIDs, they can work in “magnetometer” or “gradiometer” configurations and directly measure the absolute value of the magnetic field, which is not done by SQUIDs. It can be assumed that further improvement of the technology of superconducting materials in the form “Josephson medium” and the MMM design will bring their characteristics closer to the SQUID parameters.

MFS is currently being actively developed. The main parts of this type of sensor are: superconducting film magnetic field concentrator (MFC) and MSE based on the structure of spintronics. Studies have shown that CMFS as part of MFC from Nb film (LTSC material), MSE from magnetoresistive film on the effect of giant magnetoresistance (GMR) can have $\delta \Phi \sim 10^{-6}-10^7 \phi_0$. It is seen that this indicator is much better compared with the resolution of HTSC SQUID and is at the level of LTSC SQUID [23]. Various CMFSs that contain thin-film MFC from LTSC or HTSC and MSE from GMR films were proposed in [24-26]. One type of CMFS consists of two MFCs in the form of a square or round film ring with a tapered portion (active strip) and an MSE located between them. Rings MFC, MSE are located on the same plane of the substrate and such CMFS is called “Planar CMFS”. The other type of CMFS consists of a single concentrator ring, which is separated from the MSE by an insulating film, and is arranged as a “sandwich”, and is called a “Sandwich/CMFS”. It was shown that optimal fragmentation (nanostructuring) of the MFC active band in the form of parallel micro and nanoscale branches and cuts leads to additional increases in the magnetic field concentration coefficient and the efficiency of CMFS. In particular, the geometric dimensions of the concentrator ring and the overall dimensions of the CMFS are reduced.

In this paper, we study the combined sensor of the “Sandwich/CMFS” magnetic field, taking into account the inductance and the geometric dimensions of the hub ring. In this case, the active band of the ring of nanostructured elements is presented in the form of parallel superconducting branches and cuts having micro- and nano-dimensions.

2. Research methods
The object of study was factor $F$ of multiplication (concentration) of a magnetic field of the film MFC on the MSE with the active strip divided into parallel superconducting branches and cuts. It was assumed that $F = 1$ when there is no fragmentation, i.e., the active strip is continuous. The investigated MFS structure comprises a superconducting film ring with the narrowed active strip and an MSE from the GMR film. The active strip of the MFC overlaps the MSE separated by an insulating film (Figure 1).
Figure 1. Schematic of the CMFS and its elements: (1) superconducting MFC ring, (2) dielectric substrate, (3) MFC active strip enlarged without keeping proportions, (4) MSE, (5) isolating film, and (6) branches and (7) cuts of the active strip.

The \( F \) value was estimated in the following way. In external magnetic field \( B_0 \), the magnetic flux, which screens ring 1 (figure 1), is determined as \( \phi = A \cdot B_0 \), where \( A \) is the ring square. The screening current is \( I_s = \phi /(L+M) \), where \( L \) is the inductance of the ring, and \( M \) is the sum of mutual inductances between the superconducting MFC and MSE parts. The \( L \) value exceeds the resulting mutual inductance \( M \) by an order of magnitude and more. For a ring with the diameter \( D \) and width \( w_c \) we write

\[
I_s = \frac{\pi D^2 \cdot B_0}{4L},
\]

\[
L = \left( \frac{\mu_0 D}{2} \right) \cdot \left( \ln \left( \frac{4D}{w_c} \right) - 2 + \frac{7w_c}{2D} \right).
\]

Inductance \( L \) of the MFC ring is much higher than inductance \( L_0 \) of the active strip. When the latter consists of several branches with inductances \( L_i \) \((i=1,2,...,n\), where \( n \geq 2 \) is the number of cuts in the active strip), their resulting inductance is insignificantly higher than \( L \).

We calculated the maximum \( F \) value at different widths of branches and cuts, their number, topology, and characteristics of a superconducting MFC material. For optimal nanostructuring of the active strip and, consequently, attaining the maximum \( F \) value, we determined the magnetic fields on the MSE induced by superconducting currents in branches of the active strip. In the calculation, we took into account only the magnetic field component parallel to the substrate surface, since it strongly affects the MSE in the form of the GMR element.

We used the well-known formulas:

\[
B_i = \frac{\mu_0 \cdot I_s}{8\pi \cdot \lambda \cdot h} \left[ \int_0^0 \int_{-2h}^0 e^{-\frac{y+1}{2}} \cdot \left( \frac{y_0 - y}{y_0 - y} \right)^2 \cdot dxdy + \int_0^0 \int_{-2h}^0 \frac{e^{-\frac{y+1}{2}} \cdot \left( y_0 - y \right)}{(y_0 - y)^2 + (x_0 - x)^2} \cdot dxdy \right].
\]

\[
F = \frac{\langle B_{un} \rangle}{\langle B_0 \rangle} \cdot \frac{1}{K_L},
\]

\[
K_L = \frac{\left( \sum_{i=1}^{n+1} L_i^{-1} \right)^{-1}}{L} - \frac{w_f}{\sum_{i=1}^{n+1} w_i}.
\]
Where \( l \) and \( h \) are the half-width and half-thickness of the active strip film, respectively; \( \mu_s \) is the magnetic field constant; \( I_s/(4\lambda h) \leq J_c \), \( J_c \) is the screening superconducting current in the active strip above the MSE and acting on the latter at the point \((x_0, y_0)\) with the reference point \((0,0)\) located at the center of the upper film surface; \( J_c \) and \( \lambda \) are the critical current density and London penetration depth for the MFC film material, respectively; \( \langle B_s \rangle \) and \( \langle B_h \rangle \) are the averaged magnetic fields induced by the active strip with numerous branches and without them (continuous strip), respectively; \( K_l \) is the growth factor of the resulting inductance of the active strip; \( L \) and \( L_i \) and the inductances of the active strip and its \( i \)-th branch, respectively; \( n \) is the number of cuts in the active strip; \( n+1 \) is the number of branches in the active strip; and \( w_j \) and \( w_j \) are the total width of the active strip and the width of its \( i \)-th branch, respectively. In all calculations, we took into account the change in the inductance of the active strip during its nanostructuring (fragmentation). In (3) we assumed a strong dependence \( L_i \sim 1/w_i \), therefore the values of \( F \) we obtained are somewhat underestimated. In general, the maximum values of the concentration coefficient \( F \) changes the total inductance of the active band has little effect.

Circulating current \( I \), around the ring creates a magnetic field \( \langle B_s \rangle \parallel \) to the plane of the active band:

\[
\langle B_s \rangle \sim <K> \frac{\mu_s I_s}{w_j},
\]

(6)

Here \( <K> \) is the coefficient that reflects the non-uniform current distribution across the width of the active band. According to (3) \( <K> \sim 1 \). Then, taking into account formulas (1) - (6), you can get an approximate expression for \( F_0 \) :

\[
F_0 \approx \frac{0.24 D}{w_S \left\{\ln \left(\frac{4D}{w_L}\right) - 2 + \frac{D}{w_L}\right\}}.
\]

(7)

The physical basis of operation of our CMFS is concentration of a magnetic field on the MSE by the MFC. High magnetic field concentration on the MSE allows enhancing its relative magnetic-field sensitivity \( S_0 \) by a factor of multiplication \( F_0 \) (no fragmentation) and improving the CMFS resolution. Here, \( S_0 = \left(\frac{R_0}{R_0 - 1}\right)/B \), where \( R_0 \) is the MSE resistance in an external magnetic field, i.e., at \( B \neq 0 \) and \( R_0 \) is the resistance of the MSE without magnetic field, i.e., at \( B = 0 \). Indeed, for configurations with the MSE in the form of the GMR element with width \( w_{GMR} \) approximately coinciding with width \( w \) of the active strip, the external magnetic field variation \( \Delta B \) is reflected on the MSE under the action of the MFC as the variation \( \Delta B_{GMR} \). The ratio \( \Delta B_{GMR}/\Delta B = F_0 \) is the factor of multiplication (concentration) of the magnetic field under the action of the MFC. We may expect that the value \( F_0 \sim D/w_{GMR} \) characterizes an increase in \( S_0 \) to \( S_0 \); thus, the parameters of the MFS are improved, specifically, the minimum detected magnetic field \( \delta B \) is decreased. In the CMFS with the continuous active strip, we have

\[
\delta B \sim \frac{\delta U}{IR_0 F_0 S_0}.
\]

(8)

Here, \( \delta U \) is the minimum signal detected by the MFS and \( I \) is the MFS measuring current. It can be seen that the high \( F_0 \) value leads to improvement of the parameters of the MFS, in particular, to a decrease in \( \delta B \).
The $F$ value was calculated for different numbers of cuts with width $w_p$, insulating layer thicknesses $h_{ins}$, and $\lambda$. In the calculation, we took into account only the magnetic field component parallel to the substrate surface, since it strongly affects the MSE.

3. Results
We simulated the splitting of the active band and calculated the concentration coefficients in cases of a continuous film of the active band and its fragmentation containing nanostructured elements (nanoscale sections). In this case, only the projection of the magnetic field parallel to the substrate surface was taken into account, since it is this component that affects the MSE as an element with GMR. It was believed that in the case of a continuous active band ($n = 0$) coefficient $F = 1$. Taking into account the value of the concentration coefficients, the threshold sensitivity was estimated for the approximate CMFS.

![Diagram](image_url)

**Figure 2.** Distribution of the magnetic field along the centre of MSE for different values of the number of slots in the active band (at $\lambda = 50$ nm): a - 0, b - 2, c - 4, d - 6.
In Figure 2 shows the qualitative graphs of the distribution of magnetic fields across the width of MSE for different values of the number of cuts plotted on the active strip of a magnetic field concentrator from an LTSC film with $\lambda = 50$ nm. The abscissa axis represents the width of the active band, which coincides with the width of the MSE (see figure 1). Magnetic field values in relative values are given on the ordinate axis. The average values of the magnetic fields $<B_a>$ in the middle of the MSE thickness were determined according to (3) and they are reflected in the form of dashed lines.

It is seen that with an increase in the number of cuts the average value of the magnetic field increases (horizontal dashed line). Noticeable is the fact that a concentrator with nanostructured elements in the active band is most effective based on LTSC material, and a concentrator with a continuous active band is based on HTSC material.

Table 1 presents the calculated values $F_0$, $F$ and $F^* = F_0 \times F$ in which the data obtained from the graphs shown in Figure 2 in the case $\lambda = 50$ nm were used. Also, Table 1 shows the values of the indicated parameters obtained from similar graphs for the case of $\lambda = 250$ nm. The following values were used in the calculations: $w_p = 20$ nm, $h_{ins} = 20$ nm, $h = 25$ nm, $w_s = 4000$ nm, $h_{mcs} = 50$ nm, $D = 4$ mm, $w_c = 1$ mm and $J_c = 10^7$ A/cm$^2$.

### Table 1. Multiplication factors for different numbers of cuts of the active band.

| Multiplication factors | Numbers of cuts |
|------------------------|-----------------|
|                        | $n = 0$ | $n = 2$ | $n = 4$ | $n = 6$ |
| $F_0$ $\lambda = 50$ nm | 17 | 4 | – | – |
|                        | $\lambda = 250$ nm | 21 | 5 | – | – |
| $F$ $\lambda = 50$ nm | 1 | 3.6 | 5.5 | 6.8 |
|                        | $\lambda = 250$ nm | 1 | 2.8 | 3.9 | 4.1 |
| $F^*$ $\lambda = 50$ nm | 17 | 626 | 957 | 118 |
|                        | $\lambda = 250$ nm | 21 | 602 | 838 | 882 |

### Table 2. Estimated threshold sensitivity for CMFS with different MSE and multiplication factors.

| Multiplication factors | Threshold sensitivity CMFS $\delta B$, pT |
|------------------------|------------------------------------------|
|                        | GMR | MTJ |
| $F_0 = 174$ ($\lambda = 50$ nm) | $S_0 \sim 2$ \%/mT \[17]\ | $S_0 \sim 15$ \%/mT \[14,28]\ |
| $F_0 = 215$ ($\lambda = 250$ nm) | 11.5 | 3.8 |
| $F^* = 1183$ ($\lambda = 50$ nm) | 9.3 | 3.1 |
| $F^* = 882$ ($\lambda = 250$ nm) | 1.7 | 0.56 |
| $F^* = 882$ ($\lambda = 250$ nm) | 2.3 | 0.76 |
Note the fact that follows from table 1: when the diameter of the concentrator ring is $D = 4$ mm the nanostructuring of its active band is $F' \sim 1200$, the concentration factor $\sim 1300$ is realized in the concentrator with continuous active band and $D = 25$ mm [27]. One can see the obvious advantage of a concentrator with an active band with nanostructured elements relative to a continuous active band.

It is of interest to estimate the threshold sensitivity $\delta B$ of the sensor according to (8). Here we take into account the following values: $\delta U \sim 1$ nV; $IR_0 \sim 100$ mV is the voltage drop on the MSE at $R_0 \geq 1000$ Ohm, $S_0 \sim 2%$/mT is the magnetic sensitivity for the sensor based on GMR [17], and $\sim 15%$/mT for the sensor based on magnetic tunneling junction (MTJ) [14,28]. In table 2 shows the estimated $\delta B$ in which the values $F_0$ and $F'$ used from table 1.

From table 2 it follows that fragmentation (nanostructuring) of the active MFC band, which results in high values of the concentration coefficient $F'$, leads to a decrease in the threshold sensitivity $\delta B$ several times. This means improving the efficiency of CMFS. In particular, with a continuous active band ($F_0 = 174$), it is possible $\delta B \sim 3.8$ pT as in the case of nanostructuring of the active band ($F' = 1183$), the threshold sensitivity will decrease to $\delta B \sim 0.56$ pT.

We believe that a further increase $n$ will lead to an increase $F$ in the magnitude of another 1-2 orders of magnitude, relatively considered here $n = 6$. Therefore, it can be expected to decrease $\delta B$ as many times, and then the threshold sensitivity of the CMFS can be at the level of the threshold sensitivity ($\delta B \sim 10$ fT) SQUID. Due to the small size of the concentrator, the threshold magnetic flux sensitivity of the considered CMFS can be expected at a level of $\delta \phi \leq 10^{-4} \phi_0$.

The noise characteristics of the CMFS are important. They are mainly determined experimentally and depend on many factors, including the design of the sensor. In many cases, the spectral density of the noise of a real sensor is much higher than its level determined by thermal limitations. For example, for CMFSs similar to those considered by us, the levels of spectral densities of thermal noise at temperatures of $\sim 77$ K and $\sim 4$ K, respectively, are $0.008$ pT/Hz$^{1/2}$ and $0.002$ pT/Hz$^{1/2}$ [29]. It can be seen that our estimates $\delta B$ are much higher than the level of its possible limitation from below by thermal noise in a wide range of frequency bands ($\lesssim 1000$ Hz). Therefore, it can be assumed that there is a potential for further reduction $\delta B$ by increasing the number of cuts, of course, to the level of intrinsic noise CMFS.

On the other hand, the potential for improving sensor performance can be used to reduce the size of the concentrator ring. Indeed, in (8), when the active band is fragmented, instead of $F_0$, it should be used $F' = F_0 \times F$ , then for the fixed $\delta B$ it should be taken $F_0$ in $F$ times less. According to (7), the value $F_0$ is approximately determined by the ratio of the diameter of the ring to the width of the active strip, therefore a decrease $F_0$ means a decrease in the size of the diameter of the ring by a factor of $F$. For example, in the case of $D = 4$ mm and $F_0 = 174$ we have $\delta B \sim 11.5$ pT (see table 1), and in the case of nanostructured elements in the active band at the same level of $\delta B \sim 11.5$ pT, we should take $D = 4/6.8 \sim 0.6$ mm. Received a significant reduction in the size of the hub ring and the size of the CMFS. Obviously, the value of $w_L$ will also decrease.

Reducing the overall dimensions of the MFC and the CMFS as a whole is an important positive point in the way a matrix with numerous sensors can be made. The matrix can significantly improve the resolution, as shown by the example of using the system of more than one thousand MTJ [30].

Apparently, our proposed method of nanostructuring the active strip of a film superconducting concentrator is useful in a magnetic flux transformer used in SQUIDs. For example, the head helmet of the "Elekta Neuromag" magnetoencephalograph contains $\sim 300$ pieces of SQUIDs [31]. Assuming the possibility of reducing the size of SQUIDs will allow you to create a matrix with a large number of them. Consequently, the spatial resolution of the magnetic encephalograph and the quality of diagnostics will increase.
4. Conclusion
The obtained quantitative values of the concentration coefficients, the threshold sensitivity or the dimensions of the combined magnetic field sensor refer to the case when the screening current in the active strip of the concentrator is distributed similarly to the Meissner screening current. Therefore, depending on the type of distribution of the shielding current, the quantitative values given in tables 1 and 2 can vary greatly. Despite this, the main qualitative result of the study is that nanostructured elements in the active band of a magnetic field concentrator increase efficiency, i.e. lowers the threshold sensitivity of the combined magnetic field sensor.

Also the most important points are the following:
• nanostructured elements several times reduce the geometric dimensions of the concentrator, and thus the size of the sensor;
• with an increase in the number of elements (cut width 20 nm) in the active band of the concentrator, the efficiency of the sensor increases — its threshold sensitivity decreases;
• under the same conditions, a combined magnetic field sensor with a low-temperature superconductor film concentrator is more efficient than a high-temperature superconductor film sensor.

A combined magnetic field sensor with a solid hub has a high potential for detecting ultra-weak magnetic fields. It exceeds the threshold sensitivity of the magnetic field sensors of the first type mentioned above, and is probably close to the most sensitive sensor of the second type - SQUID [20,22,23]. Moreover, the combined magnetic field sensor with nanostructured elements in the active band of a concentrator investigated by us may have a higher potential for sensitivity than a concentrator with a continuous active band, and apparently it can be an alternative to SQUID.

Modern medicine requires biocompatible materials and nanomaterials, as well as systems containing ferromagnetic or superparamagnetic particles, carbon nanotubes, and others. As well as non-invasive diagnostics due to the registration of biomagnetic fields and the control of active implanted devices (artificial heart, various stimulants, measurement of blood flow velocity, etc.). All of the above are sources of ultra-weak magnetic fields. These tasks and others will probably also be solved by using combined magnetic field sensors with nanostructured elements.

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\textbf{Acknowledgements}

The authors are deeply grateful to A. Mironyuk and N. Shichkin for their help in programming calculations. This paper was done with the assistance of government assignment Ministry of Education and Science of the Russian Federation (№ 20.9216.2017/6.7).