SQUID-Based Setup for the Absolute Measurement of the Earth's Magnetic Field.

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SQUID-based magnetic sensors exhibit outstanding sensitivity and bandwidth. But, due to their periodic voltage-flux characteristic, they are not suited for absolute magnetometry. Furthermore, their application in unshielded environment is challenging, because magnetic transients may interrupt the flux locking loop (FLL) and introduce step-like shifts into the output signal that cannot always be corrected by postprocessing of the acquired data.

The sinusoidal-like voltage-flux characteristic of a SQUID is unique (and thus suited for absolute magnetometry), if the absolute value of the magnetic field strength B is below a certain threshold value B_{max}, which depends on the effective area A of the SQUID:

$$\left|B\right| < \frac{\Phi_0}{2A} = B_{\max} . \qquad (1)$$

To achieve both, a large B_{max} and a good sensitivity, we propose to use a cascaded SQUID setup as depicted in Figure 1. It consists of several coplanar SQUID magnetometers with largely different effective pickup areas that are integrated on a single chip. Because of their spatial proximity and equal orientation, each SQUID of the cascade measures approximately the same magnetic field strength.

The effective area of the smallest SQUID (herein named reference magnetometer) is about $A_R \approx 0.05\ \Phi_0/\mu T$, which corresponds to $B_{max} \approx 10\ \mu T$. The absolute output of the reference SQUID is now used to calculate the branch of the voltage-flux characteristic on which the next SQUID in the cascade (the intermediate SQUID) is locked, resulting in a more precise absolute value of the measured magnetic field component since the effective area of two consecutive SQUIDs in the cascade increases by about two orders of magnitude. This principle is repeated up to the most sensitive SQUID, which determines the noise level of the final measurement value. The white noise level of the sensitive SQUID in our setup is about $B_{n,s} = 6\ fT/Hz^{1/2}$. The dynamic range of the system, defined as the ratio of the maximum peak-to-peak signal amplitude to the achievable signal resolution limited by the noise $B_{n,s}$ in a 1 Hz bandwidth, is about 190 dB.

The value of $B_{max} \approx 10\ \mu T$ is actually too small for absolute magnetometry in the Earth's magnetic field ($B_{Earth} \approx 50\ \mu T$). But for many applications, a redesign of the reference SQUID is not necessarily needed. If the reference SQUID is not locked on the correct branch, the error is $n \cdot \Phi_0/A_R \approx n \cdot 20\ \mu T$, where n is an unknown integer. This quantized offset can quite easily be estimated prior to the measurement, for example by a rotation of the setup or a by measuring the offset inside a simple magnetic shielding.

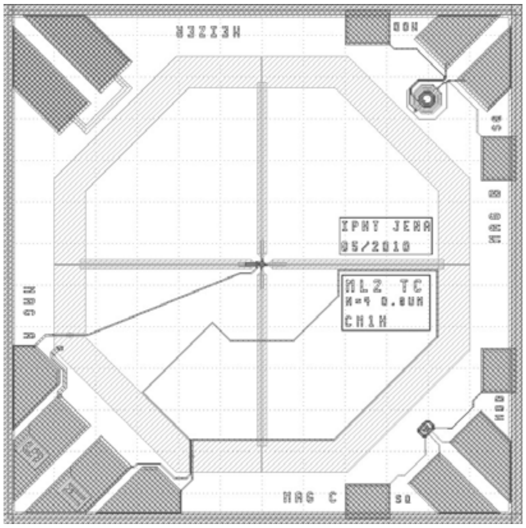

Figure 1: View of the square 2.5 mm chip with three SQUID magnetometers. The sensitive four loop magnetometer is situated in the centre of the chip. The intermediate and the reference magnetometer are located in the upper and lower right corner, respectively. The chip is equipped with a heater in the upper left corner.

SQUID	**S**	**I**	**R**
V_{PP} **[µV]**	190	160	340
β_L	4.3	0.8	0.2
β_C	0.52	1.05	0.7
B_n **[fT/Hz$^{1/2}$]**	6	250	$12 \cdot 10^3$
A_x **[Φ_0/µT]**	334.3	3.7	-0.05
A_y **[Φ_0/mT]**	0	-5.3	-0.32
A_z **[Φ_0/mT]**	0	-6.1	0.31

Table 1: Characteristic parameters of the sensitive (S), intermediate (I) and reference (R) SQUID: voltage swing V_{PP}, inductance parameter $\beta_L = 2\pi I_C L/\Phi_0$, McCumber parameter β_C and white magnetic field noise B_n. The effective areas are specified by their vector components A_x, A_y and A_z since they are not sufficiently parallel. The x direction is defined by the sensitive SQUID.

Absolute magnetometry requires sensors without closed superconducting loops, which would freeze an unknown amount of flux during cool down. Thus, our sensors are designed without any flux transformer circuitry. All SQUIDs were fabricated with our 0.8 µm cross-type Josephson junctions. Due to their small width, the critical field strength for flux trapping in the junction region could be shifted to 3.9 mT during cool-down. Some important SQUID parameters are summarized in Table 1.

Experiments with a cascade-based one-axis magnetometer revealed the existence of an on-chip 3 x 3 crosstalk matrix that can be explained by the coupling of each feedback coil to each SQUID of the chip. We could correct this effect by postprocessing after the experimental determination of the crosstalk coefficients. Furthermore, it turned out, that the directions of field sensitivity of the cascaded SQUIDs are not sufficiently parallel to guarantee the correct working of the cascade principle if the applied magnetic field contains a strong component parallel to the chip plane. This effect is expected to originate in parasitic areas contained in the multilayer structure of the SQUIDs. In a future three-axis setup, these parasitic area contributions will also be compensated by postprocessing.

For the experimental verification of the correct functioning of the one-axis cascade magnetometer, magnetic field modulations with amplitudes exceeding 50 µT were applied perpendicular to the chip surface. The maximum measured deviation between the sensitive and the intermediate SQUID was about 0.3 nT, corresponding to about 0.1 Φ_0 of the sensitive SQUID. For absolute magnetometry, it is further necessary to calibrate the magnetic offset of the SQUID cascade, which is caused by trapped flux, self-fields of the bias currents and offsets in the SQUID readout electronics.

Further research will focus on the implementation of a three-axis absolute magnetometer and the investigation of the long term stability of its magnetic offset after thermal cycling.