# Integration of the electronics and batteries inside the hollow core of a search coil

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A novel design of a miniature search coil magnetometer is proposed based on the integration of the electronics and batteries within the hollow core of the search coil. In contrast with conventional designs, where the search coil and its electronics have individual housings and electrostatic shields, this paper presents a design in which the core of the search coil serves both as the housing and the magnetic shield for the electronics and batteries. Moreover, the electrostatic shield of the search coil also shields the electronics and batteries. We found that a thin-wall tube core with sufficient permeability is able to replace a solid rod core without decreasing the average flux sensed by the coil winding. In addition, the outer diameter of the tube core can be increased beyond its optimum size to provide more space for the electronics and batteries without considerably affecting the search coil resolution. To validate the effectiveness of this new design, a miniature search coil magnetometer was built and tested for very low frequencies and ultra-low power consumption. © *2010 American Institute of Physics*. [doi:10.1063/1.3337750]

## I. INTRODUCTION

Reducing the size and weight of sensors and electronics is very important today for many applications, such as space research and magnetic anomaly detection.[1–6] This is especially important in the cases where the sensors and their electronics are not integrated within a single housing. An example can be miniature search coils magnetometers, where the size of the electronics and batteries is comparable with the size of the sensor. In typical modular designs,[1–6] both the search coil and the electronics have individual housings and individual electrostatic shields. The electric wiring between the search coil and the electronics should also be shielded. All this increases the size, weight, and the complexity of the entire magnetometer. In designs, where the search coil and the electronics share the same housing, the latter is larger than needed for the search coil alone.

In this work, we propose an original design where all the magnetometer components, including the search coil, its electronics, and batteries are integrated within a single housing that is no larger than what is needed just for the search coil. Moreover, the search coil itself serves as both the housing and the magnetic shield for the electronics and batteries. This is obtained by replacing the solid rod core of the search coil with a thin-wall tube core and integrating the electronics and batteries inside this tube core (see Fig. 1). We found that a thin-wall tube core with sufficient permeability can keep the same average magnetic flux through the search coil winding. In addition, increasing the outer diameter of the tube core beyond its optimum value, to provide more space for the electronics and batteries, does not significantly affect the

search coil resolution. To validate the effectiveness of this new design, it was tested on a miniature search coil magnetometer[3] optimized for very low frequencies and ultra-low power consumption.

## II. METHOD

### A. Comparison of the magnetic fluxes averaged over the length of the rod and tube cores

Let us start from a comparison of the magnetic fluxes averaged over the length of the rod and tube cores of a search coil similar to Ref. 3 that has a 50 mm length, 30 mm diameter, and employs disk-shape flux concentrators of a 30 mm diameter and 2 mm thickness.

To find the relative difference between the fluxes as a function of the wall thickness, $t$, of the tube core (see Fig. 2),
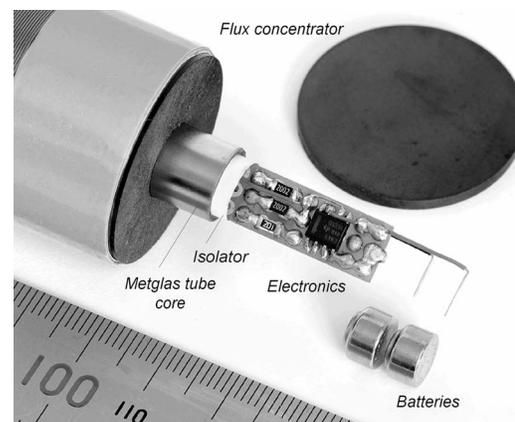


FIG. 1. Experimental model of the search-coil magnetometer. The magnetometer is disassembled to show the integration of its electronics and batteries inside the hollow core. (The alignment of the assembled flux concentrators and core is shown in the insert of Fig. 2.)

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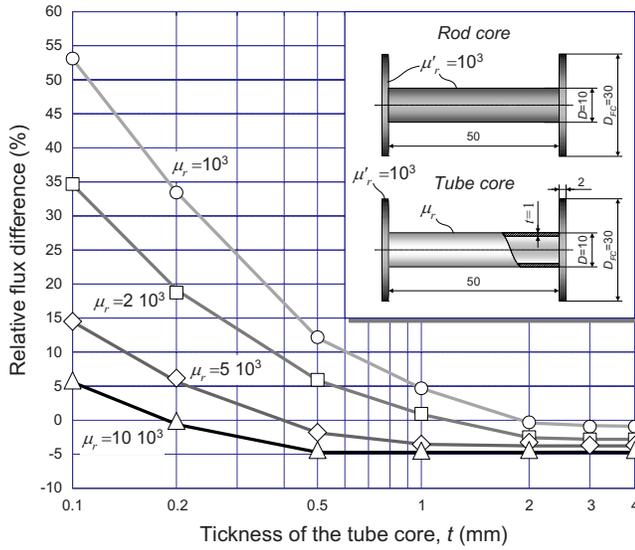b)Electronic mail: paperno@ee.bgu.ac.il.

FIG. 2. (Color online) Relative difference between the magnetic fluxes averaged over the length of the rod and tube cores as a function of the tube core thickness.

we used a Maxwell SV program based on the finite-element method. In our simulations, the relative permeability of the rod core and the flux concentrators is fixed at a typical for ferrites value of $\mu'_r = 10^3$, and the relative permeability of the tube core, $\mu_r$, is a parameter. Figure 2 shows that the permeability of a thin-wall tube core should be high enough to keep the same average magnetic flux as inside the solid, rod core of the same diameter and length. For example, a 10 mm outer diameter tube core has to have at least an about $10 \times 10^3$ relative permeability if its thickness is 0.2 mm.

Considering the results of Fig. 2, we can conclude that it is possible to replace a rod core with a thin-wall tube one that has a high enough permeability and keeps the same average magnetic flux through the search coil winding and to use the interior of the tube core for the electronics and batteries. Our numerical simulations with Maxwell SV have shown that even relatively wide, 50 $\mu$m air gaps between the tube core and the flux concentrators reduce the average flux through the core by less than 13%.

## B. Optimum sensitivity threshold as a function of outer diameter of the thin-wall tube core

The search-coil sensitivity threshold (or resolution) at low frequencies can be found as follows:[1–3]

$$B_{\min} = \frac{\sqrt{4kTR + e_n^2 + i_n^2 R^2}}{2\pi f \cdot \mu_{\mathrm{app}} \frac{\pi}{4}[D^2 - (D - 2t)^2]}, \tag{1}$$

where $4kTR$ is the power spectral density of the coil thermal noise, $k$ is the Boltzmann constant, $T$ is the absolute temperature, $R$ is the coil resistance, and $e_n$ and $i_n$ are the voltage and current noise densities of the preamplifier,[1] $f$ is the frequency, $n$ is the number of turns, $D$ is the outer diameter of the tube core, and $t$ is the thickness of the tube core.

To obtain in Eq. (1) the apparent permeability, $\mu_{\mathrm{app}}$, of the tube core, we assume that the relative permeability of the
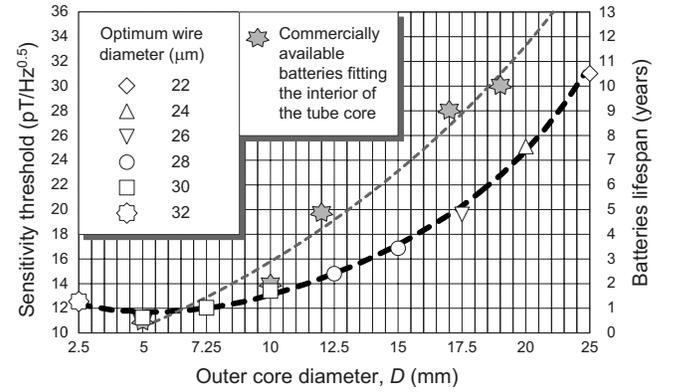


FIG. 3. Magnetometer optimization: theoretical sensitivity threshold, calculated at 1 Hz, and the magnetometer batteries lifespan as a function of the outer diameter of the tube core.

tube core material is high enough, and the average magnetic flux through the tube core material equals to that of the equivalent rod core. This leads us to

$$\mu'_{\mathrm{app}} \frac{\pi}{4} D^2 = \mu_{\mathrm{app}} \frac{\pi}{4}[D^2 - (D - 2t)^2], \tag{2}$$

where $\mu'_{\mathrm{app}}$ is the apparent permeability of the rod core with the flux concentrators,[2,3] $t$ is the thickness of the tube core,

$$\mu'_{\mathrm{app}} = \frac{\mu'_r}{1 + \mu'_r \cdot N \cdot \dfrac{D^2}{D_{\mathrm{FC}}^2}}, \tag{3}$$

$N$ is the demagnetizing factor of a rod[3] with the diameter equal to that of the flux concentrators, $D_{\mathrm{FC}}$, and with the length equal to the total length of the search coil, including the flux concentrators, $\mu'_r$ is the relative permeability of the rod and the flux concentrators.

From Eqs. (2) and (3),

$$\mu_{\mathrm{app}} = \frac{\mu'_r}{1 + \mu'_r \cdot N \cdot \dfrac{D^2}{D_{\mathrm{FC}}^2}} \cdot \frac{D^2}{D^2 - (D - 2t)^2}. \tag{4}$$

To find $B_{\min}$, we use Eqs. (1)–(4), where we fix $D$ and $t$, fix the noise of the preamplifier, limit the search coil length and diameter, vary $n$ and the wire diameter by small steps, calculate $B_{\min}$ for each set of variables, and choose its minimum value. Then we plot $B_{\min}$ in Fig. 3 as a function of a set of $D$. $B_{\min}$ in Eq. (1) as a function of the outer diameter of the tube core provides us with an indication of how much we sacrifice the resolution relative to its best possible value at $D = 5$ mm (see Fig. 3) if we decide to increase the outer and inner core diameters to provide more space for the batteries.

Figure 3 shows the results of the optimization for a search coil with the total length and the diameter not exceeding 54 and 30 mm, respectively, the thickness of the tube core of 1 mm, and an OPA333 preamplifier with a 55 nV/$\sqrt{\mathrm{Hz}}$ voltage and 100 fA/$\sqrt{\mathrm{Hz}}$ current noise densities.

One can see from figure Fig. 3 that increasing the outer diameter of the tube core does not too strongly affect the

magnetometer resolution. For example, a twofold increase, from 5 to 10 mm, decreases the resolution only by 20%: from 10.73 to 12.81 pT/Hz$^{0.5}$ at 1 Hz.

On the other hand, a twofold increase in the outer diameter of the tube core is very substantial in terms of increasing its interior space, which can be occupied by the electronics and batteries. Considering that the electronics can be miniaturized and most of the interior can be devoted to the batteries, we estimated in Fig. 3 the batteries lifespan as a function of the outer diameter of the tube core. One can see from this figure that for a 10 mm outer core diameter, the batteries lifespan can be as long as two years, instead of half a year for a 5 mm diameter. For a 17 mm diameter, the batteries lifespan can be as long as nine years, at the expense, however, of about 60% decrease in the magnetometer resolution.

## III. EXPERIMENT

To verify our theoretical results, we constructed an experimental magnetometer model shown in Fig. 1. This model is optimized for a 40 $\mu$m wire diameter, instead of the 30 $\mu$m wire providing the best possible resolution, to alleviate on the coil winding. The resulting loss in the theoretical value of the resolution is about 10%: 14.1 against 12.8 pT/Hz$^{0.5}$ at 1 Hz. The wire has been wound on a 49 mm long plastic bobbin with a 10 mm diameter opening for the core. The outer winding diameter is 30 mm, the total number of turns is 229 515, and the wire resistance is 219 k$\Omega$.

To manufacture the tube core, we used a 50 mm wide, 22 $\mu$m thick Metglas 2705M tape. The tape has been rolled to form a 50 mm long tube with a 10 mm outer diameter and 1 mm wall thickness (see Fig. 1). Disk-shape ferrite flux concentrators of a 30 mm diameter and 2 mm thickness were attached to the core. The search coil inductance and self-resonant frequency are 4654 H and 177 Hz, respectively, and the corresponding stray capacitance is 174 pF. The search-coil sensitivity at 1 Hz is 6.4 nV/pT. An additional single-layer, 31-turn winding is used to apply magnetic feedback. The tube core is connected to the ground potential of the electronics.

Although rolling the Metglas tape results in the circumferential, not axial, direction of the tube core anisotropy, our experiments have shown that the tube core permeability is high enough to keep the average flux through the tube core not below that of the rod core. A thin-wall ferrite core with a 10$^3$ relative permeability (the worst case for the material used for the flux concentrators) would not keep the magnetometer resolution at the same level. Although, the resolution decrease would be low, about 5% according to Fig. 2.

The magnetometer electronics comprises a preamplifier similar to Ref. 3. It is already quite miniature (see Fig. 1), but can easily be miniaturized still further, leaving enough space inside the core for four pairs of the GP393 button cell batteries. These batteries would have an about two-year lifespan supplying the OPA333 preamplifier at its quiescent current of 17 $\mu$A. (For simplicity we used in our experimental model only a single pair of the batteries.)

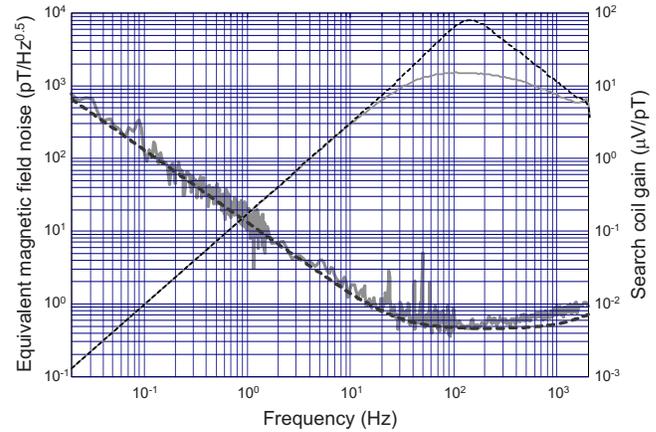Our experimental results (see Fig. 4) are in very close



FIG. 4. (Color online) Equivalent magnetic field noise of the search coil magnetometer and its frequency response. The thick solid line represents the noise measurements and the thick dashed line represents the theoretical noise estimation. The thin solid line represents the frequency response with magnetic feedback and the thin dashed line represents the frequency response with no feedback.

agreement with the theoretical calculations. At 1 Hz, the magnetometer equivalent magnetic field noise is 14.3 pT/Hz$^{0.5}$, which is very close to its theoretical estimation of 14.1 pT/Hz$^{0.5}$. The noise frequency behavior also very well fits its theoretical prediction.

## IV. CONCLUSIONS

An original design of miniature search coil magnetometers has been treated theoretically and tested experimentally. It has been shown that a solid, rod core of a search coil can be replaced by a thin-wall tube one. This does not reduce the magnetic flux through the search coil winding, provided that the tube core permeability is relatively high. The interior of the tube core is used to integrate the magnetometer electronics and batteries. Thus, the search coil itself serves as both the housing and the magnetic shield for the electronics, batteries, and all the internal wiring. This substantially reduces the size, weight, and complexity of the design and improves its electromagnetic compatibility. The suggested design can also be advantageous for accommodating only the electronics inside the hollow core of a search coil in applications where the electronics is connected to external power supply.

The suggested design is especially effective for miniature and ultra-low power inductive magnetometers. For such magnetometers, a 5 mm diameter, 50 mm long hollow core accommodates enough batteries to provide a 0.5 year continuous operation, without any reduction in the magnetometer maximum resolution. A 10 mm diameter core provides a two-year life span at the expense of a 20% reduction in the resolution.

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