Development of High-Sensitivity Fluxgate Magnetometer Using Single-Crystal Yttrium-Iron Garnet Thick Film as the Core Material

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LONG-TERM GOALS

Traditionally, a fluxgate sensor is made of metallic magnetic ribbons by which the second-order harmonics is characterized in relation to an imposed dc field. Resolution of the sensor device is limited by Barkhausen noise generated in the core region. In contrast to the conventional approach we propose to perform fluxgate operation coherently involving detection of the generated harmonics of all orders. As such, noise influence is minimized, since noise can only add to the detection scheme incoherently. In order to achieve this goal we choose to work with insulator cores, such as single-crystal yttrium-iron-garnet (YIG) thick films. In the absence of eddy-current damping, high-order harmonics are not attenuated in the core region, allowing them to be effectively included as coherent detection. Our long-term goals are to fabricate efficient fluxgate sensors using YIG films as the core material providing the following advantages: reliability, ruggedness, and economy. Most importantly, we expect our new sensor devices would result in a sensitivity one or two orders superior to the existing devices.

OBJECTIVES

The objectives of the research are to develop a new class of fluxgate magnetometers using insulator YIG as the core material measuring and analyzing the gated signal in the coherent scheme. As such, noise content is reduced and the sensitivity of the device increased. We expect that our research products can ultimately compete with the more complicated and costly SQUID fluxmeter operating at liquid helium temperatures.

APPROACH

We will first fabricate prototype fluxgate magnetometers using insulator YIG films as the sensing-core material. High-order harmonics will be measured and included in the detection scheme in a coherent manner so as to increase the signal-to-noise ratio. Alternatively, signal autocorrelation processors are employed so that high-order coherent detection is performed in digital form. Fluxgate performance will be compared and analyzed based on different core materials, including metals, metallic glasses, and insulators. The prototype device will be further miniaturized, improving temperature stabilization, reducing power requirement, and simplifying software manipulation to allow for optimal performance. The prototype will include all necessary electronics miniaturization, improved ruggedness, reliability in performance, and lower fabrication costs.

Report Documentation Page

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14. ABSTRACT
Traditionally, a fluxgate sensor is made of metallic magnetic ribbons by which the second-order harmonics is characterized in relation to an imposed dc field. Resolution of the sensor device is limited by Barkhausen noise generated in the core region. In contrast to the conventional approach we propose to perform fluxgate operation coherently involving detection of the generated harmonics of all orders. As such, noise influence is minimized, since noise can only add to the detection scheme incoherently. In order to achieve this goal we choose to work with insulator cores, such as single-crystal yttriumiron-garnet (YIG) thick films. In the absence of eddy-current damping, high-order harmonics are not attenuated in the core region, allowing them to be effectively included as coherent detection. Our long-term goals are to fabricate efficient fluxgate sensors using YIG films as the core material providing the following advantages: reliability, ruggedness, and economy. Most importantly, we expect our new sensor devices would result in a sensitivity one or two orders superior to the existing devices.

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WORK COMPLETED

We have built a magnetically shielded chamber for magnetometer measurements, whose structure is shown in Fig.1. In Fig.1 the outer wall of the chamber was made of 2 sheets of mu-metal. Each sheet of mu-metal measures 14" wide, 30" long, and 0.021" thick. These mu-metal sheets wrap around sections of PVC pipes, ID 4.5" and OD 5.0", fastened with steel clamps. The shielded zone, which serves as the magnetometer chamber, locates near the center of the mu-metal roll. The chamber was covered from above and below, respectively, by 4 pieces of PVC-pipe spacers of 1" long, stacked together and separated by mu-metal disks of diameter 5.0". Thus, the magnetometer chamber protects the shielded zone against external magnetic-flux penetration by roughly 4 layer thickness of the mu-metal sheets, from top, bottom, and surrounding.

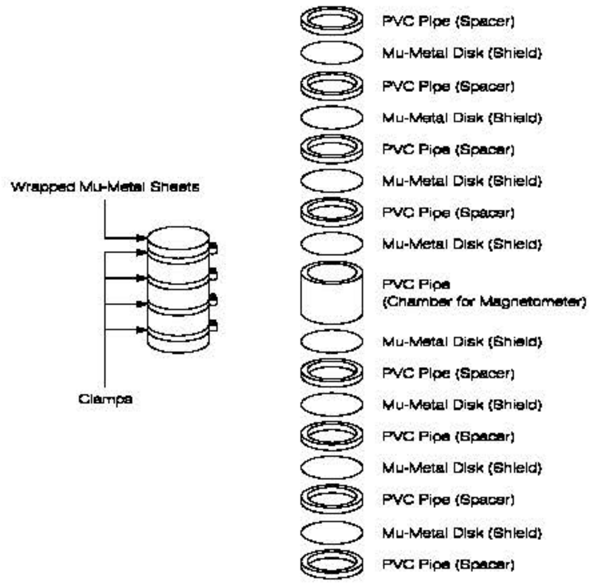

Figure 1: Fabricated Magnetic Shield

In order to avoid building many excitation coils for different core samples, we prefer to universally apply one excitation coil for all of the core samples, not only because of the implied conveniences, but also the resultant uniformity that core samples can be compared under an equal basis. For this purpose we have modified the ring-shaped core geometry of the traditional setup so that the core materials can now be loaded into and unloaded away from the system arbitrarily with ease. That is, the two halves of the excitation coil in a traditional setup are built separately, and the core is also split in two halves accordingly to be inserted in the corresponding parts of the excitation coil. Flux-closure condition needs to be satisfied as well so as to lower the excitation currents required to saturate the core material.

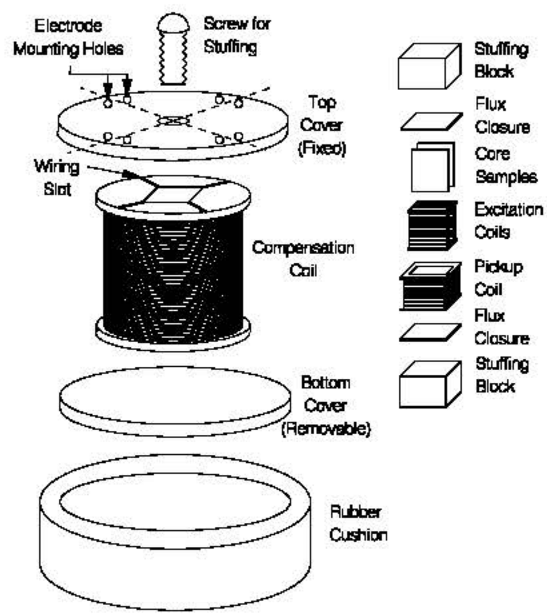

Figure 2: Fabricated Fluxgate Setup

Fig.2 shows such a modification. In Fig.2 the pickup coil remains the same as in a traditional setup. However, the excitation coil now wraps around two identical reels, or coil supports, deployed in parallel to be inserted inside the pickup coil. A pair of core samples in the form of identical slabs are inserted inside these two halves of the excitation coil. Two pieces of flux-closure slabs or arms are placed at the two ends of the cores forming a closure contour for the flux. Since the flux-closure slabs play no role in the fluxgate operation, it can be fabricated using a different material other than the core material, so long as it is magnetic soft capable of carrying or conducting all of the magnetic flux generated in the core region. The operation of the fluxgate magnetometer shown in Fig.2 is thus identical to the traditional ring-core device, which can now be applied to different sample cores in a universal manner.

Fig.2 also shows a compensation coil, or field-offset coil, capable of nulling the residual field appearing in the core region. The fluxgate assembly, including the pickup coil, the excitation coils, the sample cores, and the flux-closure slabs, is inserted inside the compensation coil. Coil wires are led out at the top cover with grooves, and the bottom cover is removable, allowing the sample cores to be loaded and unloaded. A stuffing screw is shown at the top cover, together with two stuffing blocks, it pushes against the flux-closure slabs forming tight contact with the core materials. A rubber cushion is used so as to reduce mechanical vibration. The fabricated shielding pipe, the compensation coil, the pickup coil, and the excitation coils, are shown in Fig.3.

Figure 3: Photo of the Fabricated Magnetic Shield and Fluxgate Coils

RESULTS

The operation of a fluxgate magnetometer requires the core material to be excited by a drive magnetic field encompassing the demagnetized and the magnetized states of the core in alternation. This generates magnetic noise, since irreversible domain-wall motion takes place appreciably at the knee near saturation, identified as Barkhausen jumps or discontinuities. Traditional detection of fluxgate signals involves the use of a lock-in amplifier phase-locked at the second harmonic frequency. This is shown in Fig.6. In Fig.6 a signal source is operating at, say, 20 KHz, feeding into a power amplifier to drive the excitation coil winding around the sensor core. The pickup coil feeds a low-noise pre-amplifier connected to a lock-in amplifier performing coherent detection at the second harmonic frequency, via the use of a frequency doubler.

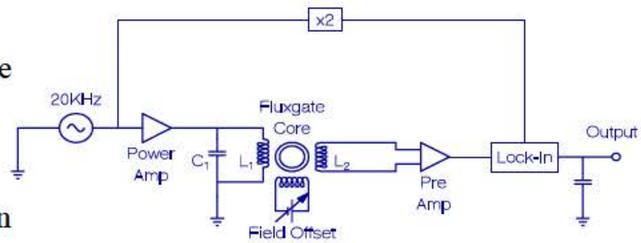

Figure 4: Traditional Fluxgate Measurements

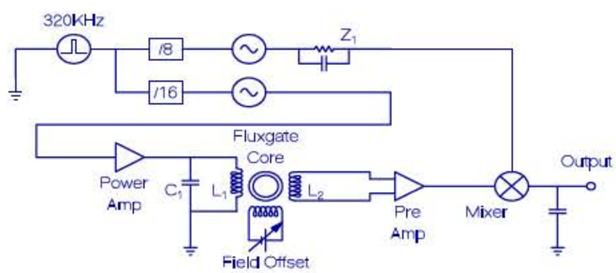

Figure 5: Alternative View of Fig.4

Fig.5 performs the same function as Fig.4, except that the lock-in amplifier is decomposed into smaller units in relation to the circuit to be discussed shortly performing high-order coherent detection. In Fig.5 a pulse generator is used providing reference for both the excitation current and the lock-in signal. To be explicit, the pulse generator is operating at 320 KHz, and the generated pulse sequence is counted down by a factor of 16 and 8 using two counters. The former pulse sequence at 20 KHz is used to trigger a signal source generating the same waveform for the driving current shown in Fig.4. The latter pulse sequence at 40 KHz triggers an oscillator generating sinusoidal second harmonic waveforms phase-locked with the excitation current. Impedance network is used to adjust the amplitude and phase of the second harmonic reference, accounting for possible time delay due to the hysteretic nature of the core material exercising magnetic excitation. Following the low-noise pre-amplifier, the output signal, or the gated signal, is mixed with the harmonic reference via the use of a mixer, and the dc output is sampled at the output terminal.

In Fig.5 it is seen that only partially the signal spectrum is used in the determination of the external field H_o expressed in the core region. That is, only the lowest harmonics of the gated signal is characterized, leaving behind all of the other higher order harmonics un-detected. The measurement scheme of Fig.5 is thus incomplete. In fact, by detecting, coherently, many orders of the harmonics of the gated signal, the resolution power of the sensor device can be enhanced, since noise voltages are uncorrelated at the higher harmonic frequencies. This forms the basis of our research.

Fig.6 shows a generalization of the circuit of Fig.5. That is, harmonics of high orders have been equally included in the detection scheme performing coherent detection. Eight such harmonic components are shown in the detection circuit of Fig.6, for example. Counters are used to count down the pulse sequence generated from a common pulse generator by a factor of 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, 7/8, feeding into respective oscillators. The fluxgate core is driven at 20 KHz, since the common pulse sequence has been counted down by a factor of 1/16. Thus, oscillators in Fig.8 generate 2nd, 4th, 6th, 8th, 10th, 12th, 14th, 16th harmonics of the drive current, respectively, connected with loading impedances and summed up in a summing amplifier. Finally, the sum signal is mixed with the gated signal from the pickup coil thereby performing coherent detection. The values of the loading impedances are chosen so that the synthesized waveform from the summing amplifier duplicates in scale the original signal waveform collected from the pickup coil. The mixing action performed in the mixer is called waveform autocorrelation, which has been known to be effective in increasing the signal-to-noise ratio in the detection of a weak signal. The detection scheme shown in Fig.6 performs high-order coherent detection so that noise generated at individual harmonic frequencies are in large averaged out.

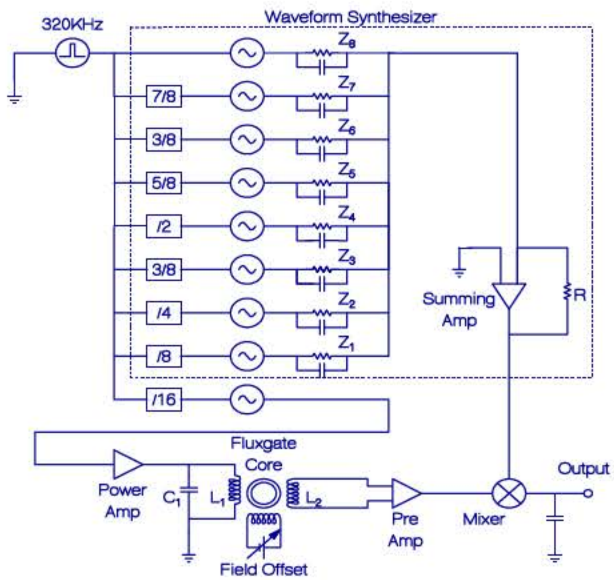

Figure 6: High-Order Fluxgate Detection

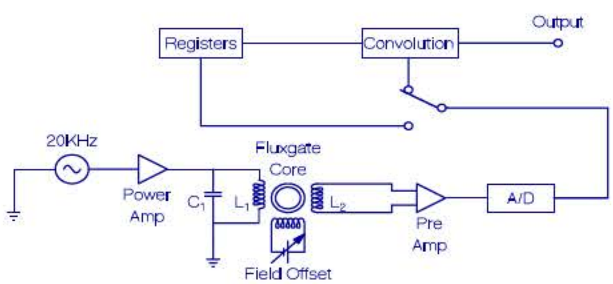

Figure 7: Fluxgate Detection Using Waveform Autocorrelation

Waveform auto-correlation can also be performed using digital processors. This is shown in Fig.7. In Fig.7 the gated signal following the pre-amplifier is fed into an analog-to-digital converter for subsequent digital analysis. The process of autocorrelation requires the waveform shape to be pre-recorded. This can be done by applying a tentative signal of sufficient amplitude from the field-offset coil, which, after averaging over many cycles, is then stored in the register bank. During this storage cycle the switch shown in Fig.7 is set on for the register bank, but off for the convolution processor. In the cycle performing waveform autocorrelation this switch is set on for the convolution processor, but off for the register bank. Thus, in measuring a weak signal H_o in the core region the gated signal from the pickup coil undergoes convolution with the pre-recorded waveform in proportion to the signal itself so as to minimize noise participation.

In conclusion we have developed a method which performs fluxgate operation involving coherent detection of harmonics of high orders. That is, high order harmonics with predetermined phases and amplitudes are synthesized (or pre-recorded) and mixed (or convolved) with the gated signal collected from the pick-up coil of the fluxgate magnetometer. Since noise can only add to the detection amplitude incoherently, the voltage signal-to-noise ratio can thus be improved by a factor of N if N harmonic components are included in the coherent detection scheme. This is true if all of these harmonic components contribute equally to the gated signal in the presence of a background containing white noise. A patent for this new fluxgate detection method is currently pending. At present fluxgate cores in the form of metal, metallic glass, and insulator have been prepared ready to be characterized using this new detection method. Both circuits shown in Figs.6 and 7 are currently under investigation. We expect that insulator cores, including YIG samples, respond more sensitively with respect to high-order components, since they attenuate less significantly than for the case if a metal core is used.

IMPACT/APPLICATIONS

Early development of fluxgate magnetometers was for airborne magnetic surveys and for submarine detection during World War II. They were further developed for geomagnetic studies (airborne, seaborne, and underwater), for mineral prospecting, and later for magnetic measurements in outer space. They have also been adapted and developed for various detection and surveillance devices, both for civilian and military use. Despite the advent of newer technologies for magnetic field measurement, fluxgate magnetometers continue to be used successfully in all of these areas, because of their reliability, relative simplicity, economy, and ruggedness. By improving the sensitivity of a fluxgate sensor, we expect new applications in the medical field, such as for magneto-cardiogram applications.

TRANSITIONS

The fluxgate sensor continues to be the preferred transducer for magnetic field vector measurements, not only because the supporting electronics is fairly simple and reliable, but also because new developments in materials sciences continue to push the noise figure to its intrinsic quantum limit. It is now approaching the point where the fluxgate device becomes an attractive alternative to the more complicated and costly SQUID fluxmeter. The increased sensitivity of the proposed device can further increase its applicability, for example, in medical imaging sensor applications. Our proposed device would result in the highest sensitivity, and, hence, imply many related applications.

RELATED PROJECTS

We have measured and analyzed the high order harmonics presented in insulator sensor cores.[1] We have analyzed for the first time a rigorous mathematical treatment of the operation of a ringcore fluxgate magnetometer.[2] Also, we have presented a theory relating the Barkhausen noises to fluxgate performance.[3] The noise performance of a fluxgate sensor have been investigated using Monte Carlo simulation in which the Preisach model was used to simulate domain wall motion.[3] We have been involved in many linear and nonlinear studies in materials and devices.[4]

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3. H. How, T. -M. Fang, C. Vittoria, "Modeling of Barkhausen Noise in Magnetic Core Material - Application of Preisach Model," J. Appl. Phys., 81(8), 5594 (1997).
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PUBLICATIONS

Our work will present in the 46th MMM Conference to be held in Seattle, Washington, November 12-16, 2001. A manuscript entitled "Fluxgate Operation Involving Coherent Detection of High-Order Harmonics," has been submitted.

PATENTS

A patent entitled "Fluxgate Signal Detection Employing High-Order Waveform Autocorrelation" is currently pending, Application Number 09/837,729, April 19, 2001.