Photonic Magnetic Field Sensor

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Abstract – Small, in-line polarization rotators or isolators to reduce feedback in fiber optic links can be the basis for excellent magnetic field sensors. Based on the giant magneto-optical (GMO) or Faraday effect in iron garnets, they with a magnetic field of a few hundred Gauss, (20 mT) for an interaction length for an optical beam of a few millimeters achieve a polarization rotation or phase shift of 45° (1/8 cycle). When powered by a small laser diode, with the induced linear phase shift recovered at the shot noise limit, we have demonstrated sensitivities at the 3.3 $nT/Hz^{1/2}$ level for frequencies from < 1 Hz to frequencies into the high kHz range. Through further improvements; an increase in interaction length, better materials and by far the greatest factor, the addition of a flux concentrator, sensitivities at the $pT/Hz^{1/2}$ level appear to be within reach. We will detail such a design and discuss the issues that may limit achieving these goals.

1. Introduction

The sensing of weak to extremely weak magnetic fields, i.e., those associated with military activity such as vehicles causing field fluctuations directly or indirectly by changing the earth's magnetic field has long been explored.[1] There is also biomagnetism, i.e., magnetic fields associated with the human heart or brain activity, see Figure 1.[2] Brain activity sensing is then called magneto-encephalography (MEG) instead of the more commonly used technique of detecting brain waves of electro-encephalography (EEG). Brain waves are at the 10^{-12} to 10^{-14} Tesla (T) level while heart beat monitors require sensitivities in the ≈ 10^{-10} T (5 to 60 Hz) range, making it necessary to perform these measurements in well shielded, screen rooms.

Two sensor concepts have attained substantial acceptance to detect weak magnetic fields. The first are fluxgate magnetometers, essentially magnetic parametric amplifiers where a magnetic field unbalances the AC fluxpaths of a transformer. Sensitivities may approach the 10^{-8} T (10 nT) level for frequencies of up to a few hertz, well short of what is often called for. A second technology that readily achieves sensitivities in excess of 10^{-14} T are superconducting quantum interference devices (Squid's). Sensitivities approach 10^{-15} T but they require complicated hardware and the Squid itself needs to be cooled to LHe temperatures.

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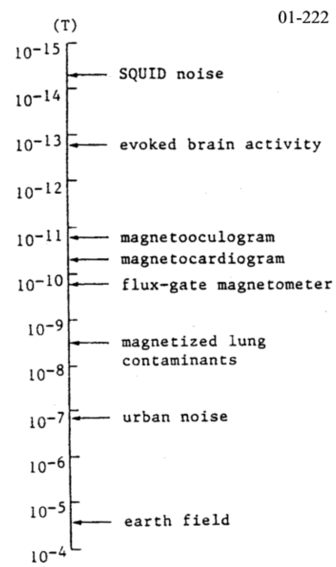

Figure 1. Typical Amplitudes of the Main Biomagnetic Fields

Two technologies that are fairly recent and that promise sensitivities midway between the fluxgate magnetometer and the Squids are those based upon the giant magneto-optical (GMO) effect in ferrimagnetic materials or YIG garnets and the giant magneto-resistance (GMR) effect in manganese based compounds.

The development of the GMO material was mostly motivated by the need for compact, in-line fiber optical isolators based on the Faraday effect, requiring only a few hundred Gauss (20 mT) in an element a few millimeter long to achieve 45° (1/8 cycle) polarization rotation (90° two way). The development of GMR devices was mostly driven by the need for better readouts for magnetic hard disc pick-ups. Both these technologies appear to have the potential for similar sensitivities. The GMO devices have better linearity, which is an important factor in a gradiometer arrangement and since the gain takes place at the photon level, it produces high level signals making it less vulnerable to EMI. The GMR devices are likely to be somewhat smaller and consume less power.

Since Visidyne's expertise lies in the area of optical sensors, a design concept based on the GMO effect will be discussed.

2. Theory/Operating Principle

The design concept for a magnetic field sensor based on the GMO effect is shown in Figure 2, in exploded form. It shows a laser diode, e.g., of the vertical cavity surface emitting laser diode, VCSEL type, because of its high efficiency at low power. Its output is collimated by a lens, and propagates through the GMO material. The vector magnetic B or H field causes a path difference and therefore a phase shift between the two, in essence left and right handed circular polarized light beams with a magnitude, in cycles of

$$\Phi = 2BVL$$

where B is the magnetic, vector field in Teslas (10^4 Gauss), V the so called Verdet constant, a measure of the magneto-optical or Faraday effect of the material, and expressed in cycles/Tesla-meter. L is the path length (in m) through the material. This phase shift is recovered by converting the two circular polarizations into two orthogonal, linear polarizations, which are separated in angle by Wollaston prism, and after passing through a polarizer/mixer, projected as a fringe pattern on a Visidyne linear array detector. The position of this pattern is proportional to the induced phase shift and is recovered by a chip-based digital phase processor.

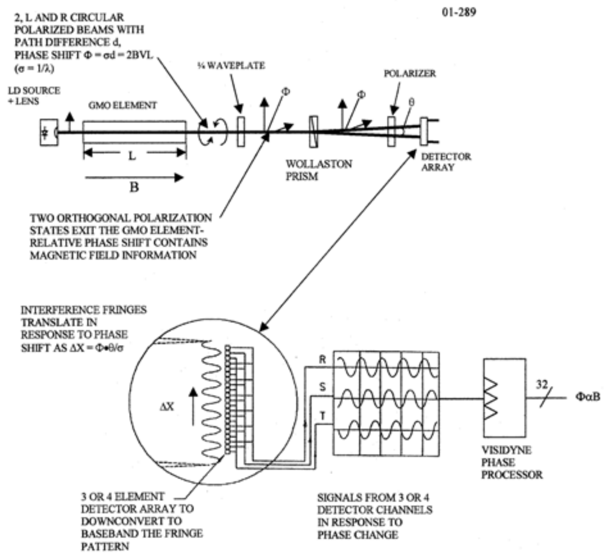

Figure 2. Concept for a B sensor based on a GMO element and a phase readout.

What makes the photonic field sensor so promising is the development of ferromagnetic materials based on iron or gallium substituted garnets or YIG's. They have Verdet constants of $\geq 1.6 \times 10^3$ cycles/Tm ($\approx 10^4$ rad/Tm) at wavelength from > 1 μm to 1.8 μm.

This compares to a Verdet constant of < 12 cycles/Tm for a high Verdet constant glass such as HOYA FR5. Thus, it is possible to build optical isolators (to minimize reflections in fiber optic based sensors or communication links which adversely affect laser diode stability) with an in-line section of GMO material (< 1 mm long, 1 mm diameter) and a magnetic field strength of ≤ 20 mT from a tiny magnet to reach a saturated Faraday rotation of 45° (1/8 cycle) or 90° (1/4 cycle) for reflected light, which is then blocked by a polarizer at 90°.

These high phase shifts combined with Visidyne's ability to measure extremely small differential phase shifts between interfering optical beams, at the shot noise level, makes it possible to measure very weak magnetic fields.

The sensitivity limit (SNR = 1) is

$$dB = d\phi / 2VL$$

where $d\phi$ is the shot noise limited phase resolution in cycles/$Hz^{1/2}$ for a given laser power P_L, detector response R_i and an overall efficiency z, for $d\phi = 1/2\pi\,(2e/zP_LR_i)^{1/2}$ cycles/$Hz^{1/2}$, $e = 1.6 \times 10^{-19}$C. Inserting some actual values of P_L = 2 mwatt, requiring 5 mwatt of electrical power, z = 0.2, detector response R_i = 1 Amp/watt at λ = 1.3 μm, V = 1.6×10^3 cycles/Tm, L = 2 mm, leads to a projected field sensitivity dB = 1.5×10^{-9} T/$Hz^{1/2}$ (1.5 nT/$Hz^{1/2}$).

An essential aspect of the design is that the B field measurement is recovered as a phase change, a ratiometric quantity, unlike the more common method as a change in intensity, i.e., through a polarizer/analyzer. This causes the sensor's response to be unaffected by source/detector 1/f noise down to very low frequencies, << 1 Hz, making it likely that ambient noise due to sensor motion/orientation and stray fields become the largest source of low frequency noise.

3. Experimental Results

That these projected sensitivities are not unrealistic can be seen from the data shown in Figure 3 and 4. This data taken by the author of this write-up a number of years back shows the results for a YIG based sensor[3]. Figure 3 shows the sensors response for an applied 1 kHz square wave magnetic field, from a Helmholtz coil, with a magnitude of ≈ 48 μT (p-p). It shows the harmonics out to frequencies > 25 kHz. Figure 4 shows an ambient, laboratory noise level measurement, showing the expected 60 Hz and its 3^{d} harmonic, 180 Hz peaks. The noise floor is ≈ 3.3 nT/Hz$^{1/2}$ for an older material with l = 0.8 mm, V = 1000 cycles/T.m, and an older phase recovery scheme. Adjusting for these factors, leads to a sensitivity of dH = 8 x 10^{-10} T/Hz$^{1/2}$, close to the projected sensitivity.

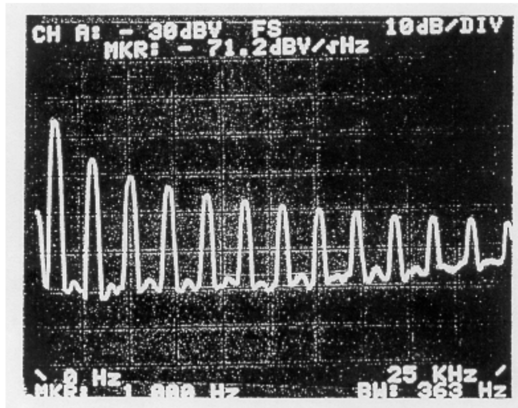

Figure 3. Sensor Response for a 48 μT, (p-p) 1 kHz Field.

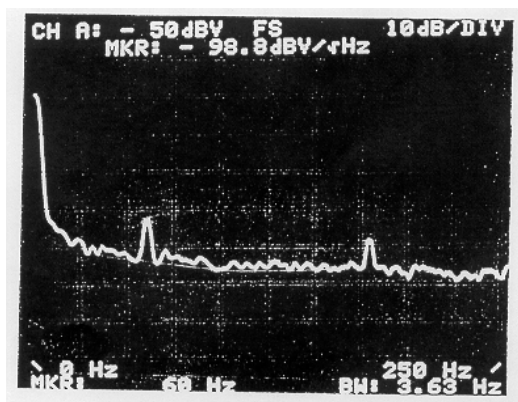

Figure 2. Sensor Output Showing Ambient Noise Peaks at 60 Hz and 180 Hz. Noise Floor ≈ 3.3 nT/Hz$^{1/2}$

4. Prognosis/Projected Performance

To make these sensors useful e.g., for battlefield activity monitoring, sensitivities at or near the pico T/Hz$^{1/2}$ are likely to be required with a bandwidth extending from < 1 Hz to > 10 kHz. In addition they should have good dynamic range and linearity so they can be deployed in a spatially dispersed, gradiometer mode of operation. Other operational factors likely to be important are working over a wide temperature range, low power consumption, small size and a data output format compatible with a sensor data collection network. A design that is projected to come close to satisfying these demands is shown in Figure 3.

It would be nearly monolithic with all elements cemented together and dimensions of ≈ 12 mm in diameter and ≈ 10 cm long.

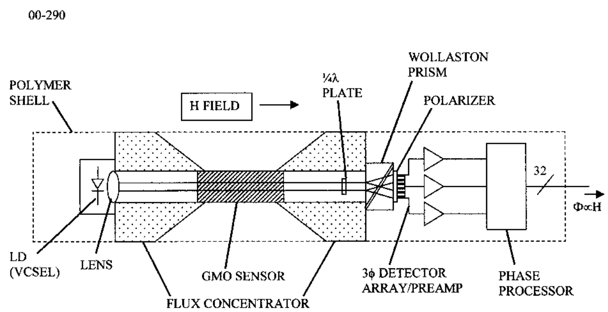

Figure 3. Sensor Design

The principal change is the addition of a flux concentrator to enhance the magnetic field in the GMO element by a factor of G. Other changes are an increase in GMO crystal lengths and materials with somewhat higher Verdet constants and additional improvements in the efficiency of the phase detector/processor. By far the greatest contribution to the sensitivity improvement is the flux concentrator. Researchers from NIST, Boulder, CO have demonstrated a gain of G > 200 (46 dB) for a GMO crystal diameter d ≈1 mm and a flux concentrator diameter of ≈ 1.2 cm.[4] An increase in crystal length from 2 mm to 5 mm should lead to a gain of 2.5, additional improvement from more recent materials and processor improvements may lead to a further improvement of a factor 3 to 4, for a total projected gain of 200 x 2.5 x 4 = 2000 (66 dB). From the previously calculated sensitivity of 1.5 $nT/Hz^{1/2}$, this leads to a projected sensitivity of < $1pT/Hz^{1/2}$.

Other Sensor Parameters

Frequency Response

The frequency response for the GMO materials appears to be well in excess of 100 MHz to 1 GHz and the sensor response will therefore be limited by the sampling rate of the phase processor of ≈ 1 to 10 MHz and by the response of the flux concentrator, likely well in excess of 100 kHz.

Linearity/Dynamic Range

GMO materials saturate at ≈ ±20 mT and are highly linear up to that point. For a response e.g., from 300 to 30 kHz, or a noise level of $\Delta B \approx 10^{-10}$ T and for G = 100, (40 dB) a dynamic range of ≈ 20 log $(20 \times 10^{-3}/10^{-10})$ – 40 db) = 120 dB. The phase processor also has in essence no dynamic range limitations and typically extends to over 32 $bits/Hz^{1/2}$.

Gradiometer Applications

How well a field sensor can be used as a 1st or 2nd order gradiometer for the purpose of spatial discrimination, critically depends on its absolute response and linearity. Both factors are expected to be satisfied for the photonic sensor.

Environment

Temperature

Material response with temperature is nearly constant over a temperature range from 20°C to > 100°C with a change of less than 1 to 3%.

Vibration

The monolithic design of the final sensor design is expected to make it robust against vibration, shock producing stray signals, However, depending on the local field gradients even small motions can generate signals and therefore may require operation as a gradiometer.

In summary, from these estimated performance values, it appears that a magnetic, B field sensor based on a GMO element and a flux concentrator has the potential to attain sensitivities at the $pT/Hz^{1/2}$ level over a wide frequency range, in a small, rugged package requiring relatively little power.

The factors that may prevent reaching these levels of performance are unaccounted for sources of noise, such as magnetic domain, Barkhausen noise from the flux concentrator, additional electronic noise, in excess of the detector shot noise, particularly at higher frequencies and quantization noise in the phase recovery process.

Other factors that could affect performance are hysteresis in the GMO/flux concentrator and noise generated by vibrations induced strains in the GMO and optical elements. e.g., through a piezoelectric mechanism.

5. References

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