

MAGNETO-OPTIC MAGNETIC FIELD SENSOR WITH $1.4 \text{ pT}/\sqrt{\text{Hz}}$ MINIMUM DETECTABLE FIELD AT 1 kHz

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The Letter demonstrates that the sensitivity of magneto-optic magnetic field sensors employing iron garnets can be increased by approximately two orders of magnitude by applying flux concentration. A minimum detectable field of $1.4 \text{ pT}/\sqrt{\text{Hz}}$ was measured when a cylindrical gallium-substituted yttrium iron garnet crystal was combined with two conically tapered nickel-zinc ferrite cylinders.

Faraday effect magnetic field sensors based on bulk iron garnets offer high sensitivity, high speed, small size, and simplicity. Earlier work has demonstrated minimum detectable fields as low as $100 \text{ pT}/\sqrt{\text{Hz}}$ at 500 Hz [1]. In this Letter, we demonstrate a technique for increasing the sensitivity of these sensors even further using the concept of flux concentration. Specifically, we combined a bulk iron garnet crystal with two conically tapered ferrite cylinders as shown in Fig. 1. Holes in

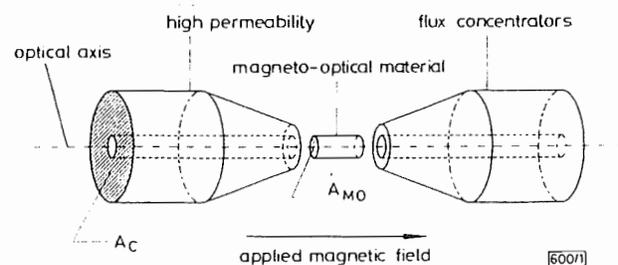


Fig. 1 Exploded view of flux concentrator magneto-optic sensor

the ferrite cylinders allow light to pass through the iron garnet crystal. In addition, the holes permit the cylindrical iron garnet crystal to be partially inserted into the ferrite cylinders for efficient magnetic coupling. The gallium-substituted yttrium iron garnet crystal used in this study measured 1.0 mm in diameter and 3.00 mm in length. The nickel-zinc ferrite concentrators each measured 25.4 mm in overall length and 12.7 mm in outer diameter. The length of the tapered portion was 12.7 mm. The faces at the tapered end of the concentrators were 3.8 mm in diameter.

The flux concentrators enhance the sensitivity of the high-permeability iron garnet through two separate mechanisms. The first effect is a modification of the iron garnet crystal's effective demagnetising factor. The sensitivity of bulk iron garnet crystals is inversely proportional to their effective demagnetising factor [2, 3]. Because of the continuous high-permeability path through the flux concentrators and the iron garnet, the three elements act magnetically as a single unit. Thus, the effective demagnetising factor for the entire system, which determines the ratio of Faraday rotation to applied magnetic field, is a function of the overall length and diameter of the magnetic system consisting of the garnet and the concentrators. The second enhancement occurs because the cross-sectional area of the concentrators is much greater than that of the iron garnet. Because the magnetic flux within the flux concentrators is forced to follow the high-permeability path going through the iron garnet, the flux density within the iron garnet is accordingly higher than in the concentrators. This constriction of the magnetic flux produces an enhancement factor approximately given by the ratio of the cross-sectional areas of the concentrators and the cross-sectional area of the iron garnet. The tapering of the flux concentrators is intended to minimise flux leakage and thus increase the efficiency of the flux constriction.

The relative frequency response of the flux concentrator sensor was measured and compared with the response obtained with the iron garnet crystal alone. Fig. 2 shows data

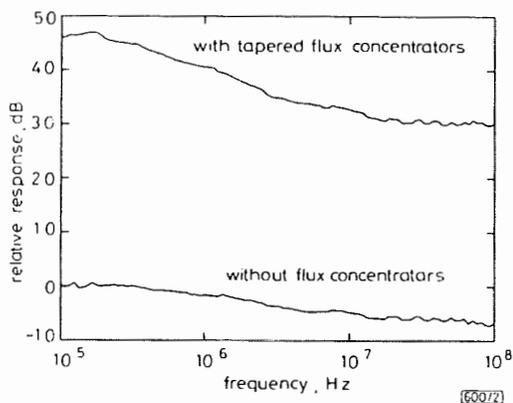


Fig. 2 Relative frequency response of gallium-substituted yttrium iron garnet crystal with and without flux concentrators

obtained when approximately 0.9 mm of each end of the 3.0 mm long iron garnet crystal was inserted into the flux concentrators. This insertion depth was used because it resulted in the greatest enhancement. Greater insertion depths weaken the signal as the iron garnet crystal becomes shielded by the concentrators. Smaller insertion depths weaken the signal because the magnetic coupling efficiency decreases. At 100 kHz, the flux concentrators enhance the signal by ~ 46 dB. A simple model based on the relative cross-sectional areas and demagnetising factors of the iron garnet crystal and ferrite cylinders predicts an enhancement of 47 dB. The frequency response of the flux concentrator sensor rolls off at significantly lower frequencies than does that of the iron garnet by itself. This behaviour may be due to the different permeability spectra of the iron garnet and the nickel-zinc ferrite.

The noise equivalent magnetic field of this sensor was measured in the following manner. Light from a diode-pumped Nd:YAG laser was collimated, polarised, and directed through the flux concentrator/iron garnet assembly. The collimated beam then reached a Wollaston polarising beamsplitter

which was oriented at 45° with respect to the input polariser. The two output beams from the beamsplitter were detected separately with InGaAs photodetectors. The signals from the detectors, each of which was coupled to a transimpedance amplifier, were fed to a sum-normalised differential amplifier. Finally, the output of the differential amplifier was fed to a spectrum analyser.

Two sets of Helmholtz coils were placed around the flux concentrator sensor. Both sets of coils were aligned coaxially with the optical axis of the system. The larger set of coils (55 cm in diameter) was used with a DC power supply to cancel the component of the earth's field along the optical axis. The smaller set of coils (13.5 cm in diameter) was driven by a current oscillating at 1 kHz. This current generated a reference AC magnetic field signal against which to compare the noise floor of the sensor system.

Fig. 3 illustrates the measured electrical spectrum when an AC field of 470 pT, RMS, was applied to the flux concentrator

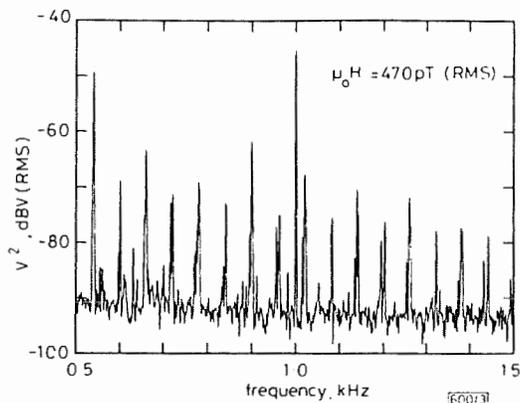


Fig. 3 Electrical spectrum of output signal of magneto-optic system based on flux concentrator sensor

sensor at 1 kHz. The signals observed at harmonics of 60 Hz consisted alternately of artefacts (probably from the detectors' power supplies) and of true signals created by ambient magnetic fields (probably from laboratory electrical equipment). Signals of the latter type disappeared when a three-layer mu-metal shield was placed around the sensor. The data of Fig. 3 demonstrate a signal-to-noise ratio of ~ 48 dB. The effective noise bandwidth of the spectrum analyser was 1.87 Hz. The resultant noise-equivalent magnetic field was $1.4 \text{ pT}/\sqrt{\text{Hz}}$. Under similar conditions, the noise-equivalent field of the same gallium-substituted yttrium iron garnet crystal used in this experiment, but without the flux concentrators, was $\sim 100 \text{ pT}/\sqrt{\text{Hz}}$ [1]. Therefore, the addition of the flux concentrators has resulted in a decrease of the minimum-detectable field by nearly two orders of magnitude. To our knowledge, this is the lowest minimum-detectable field ever reported for a Faraday-effect magnetic field sensor.

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