Chapter 34

Application of Faraday Rotation Method for Pulsed Magnetic Field Measurement

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Pulsed magnetic fields in the order of few 10s of Tesla are often generated in various pulsed power experiments like Electromagnetic welding and forming in industrial material processing, fusion research and different high energy physics experiments. In presence of intense electromagnetic radiation, conventional magnetic field measurement techniques failed to produce correct result due to various modes of EMI coupling and limited measurement range. Faraday rotation based measurement technique not only solves EMI coupling issues but also provide broad dynamic range.

34.1. Introduction

Faraday rotation or Faraday effect discovered by Michael Faraday in 1845, was the first experimental evidence that light and electromagnetism are related. It explains that the rotation of the plane of polarization of light as it propagates through a dielectric substance in a direction parallel to an applied magnetic field is proportional to the applied magnetic field (B) and length of the substance (l). The rotation of plane of polarization (θ) is generally given by the law,

$$\theta = \mathrm{VB}l \tag{34.1}$$

Where V is the material dependent constant called Verdet constant which also varies with the wavelength of light. Usually any dielectric substance exhibits Faraday rotation property, but for the measurement purpose glass media (like SF11, SF57, BK7, Terbium doped glass etc.) are used which provide wide range of linearity of Verdet constant and temperature stability.

In case of field measurement inside electromagnetic coil where magnetic field is not constant over the length of the axis rather it has a special variation, θ can be found by integrating over the length of the media.

$$\theta = \mathrm{V}\int \mathrm{B(l)dI} \tag{34.2}$$

34.2. Measurement probe design and calibration

34.2.1. Measurement Scheme

As shown in Eq. (34.1), polarization rotation (θ) is directly proportional to the applied field and length of the media, to measure applied magnetic field (B), angle of rotation of polarization plane has to be measure. In order to do that linearly polarized light is used so that its polarization angle is fixed to some reference angle when no magnetic field is applied.

Light emitting from a laser have the properties like wavelength stability, linearly polarization and high beam intensity makes it suitable for the light source of a Faraday rotation probe. Moreover, with the commercial solid state laser diode, laser module becomes light weight, portable and cost effective too.

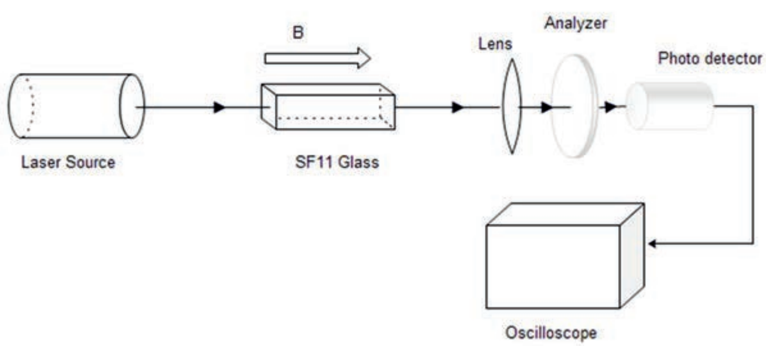

Figure 34.1. Schematic of the measurement probe.

Linear polarized beam of light emitted from laser has been guided through the Faraday rotating media (like SF11 glass) in the direction, parallel to the applied magnetic field. To measure the rotation of polarization angle, one polarizer or analyzer plate has been used which modulate beam intensity in accordance to the polarization angle of the falling beam as shown in Eq. (34.3) commonly known as Malus Law.

$$I = I_0 \, \mathrm{Sin}^2 (\phi) \tag{34.3}$$

Where I is the modulated beam intensity, I_0 is the falling beam intensity and ϕ is the angle between polarization plane and axis of the analyzer. With the help of linear photo detector modulated beam has been converted to electrical signal for recording and measuring purpose. Sometimes one focusing lens also been used in front of analyzer to reduce the beam size before entering photo detector which generally has very small detection area. With the help of Eq. (34.3), angle of rotation (θ) can be found as shown in Eq. (34.4) when analyzer is set to the perpendicular direction to the initial polarization plane.

$$\theta = \mathrm{Sin}^{-1}(\sqrt{(V/V_0)}) \tag{34.4}$$

Where, V and V_0 are the output voltage of the photo detector for the beam intensity of I and I_0 respectively.

34.2.2. Measurement Probe Design

With the help of the measurement scheme described in previous section. a portable Faraday rotation based magnetic field measurement probe has been designed and developed. To make it compact in size and light weight, solid state laser based pointer laser (wavelength 670 nm) having 100 mW power has been used as light source. For this wavelength, SF11 glass has measured Verdet constant of 12.46 rad/T-m, so the sensitivity of the probe becomes 7.14 deg/Tesla for 1cm glass length.

A commercial polarizer plate has been used here to modulate light intensity before converting it to electrical signal. BPX65 photo diode based photo detector has been developed with 1.5 kΩ load resistor which has excellent linearity with the intensity of the beam makes it suitable for the detection of the polarization angle. The detector also has 35 MHz bandwidth, makes it possible to measure pulsed magnetic field.

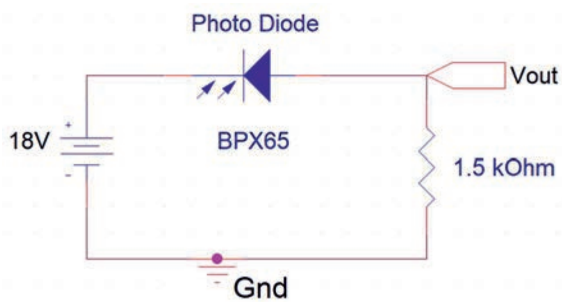

Figure 34.2. Schematic of the photo detector.

34.2.3. Probe Calibration and Field Computation

The developed probe has been calibrated by measuring field inside a long solenoidal coil having length to diameter ratio 20, where central field can be calculated by using mathematical derivation as shown in Eq. (34.5).

$$B_x = \mu_0 \frac{N}{2l} I \left[\frac{x-x_1}{\sqrt{(x-x_1)^2+R^2}} - \frac{x-x_2}{\sqrt{(x-x_2)^2+R^2}} \right] \tag{34.5}$$

Where, B_x is the field at x distance from one end and l is the total length of the solenoid, R is the radius of the solenoid and N is total number of turns.

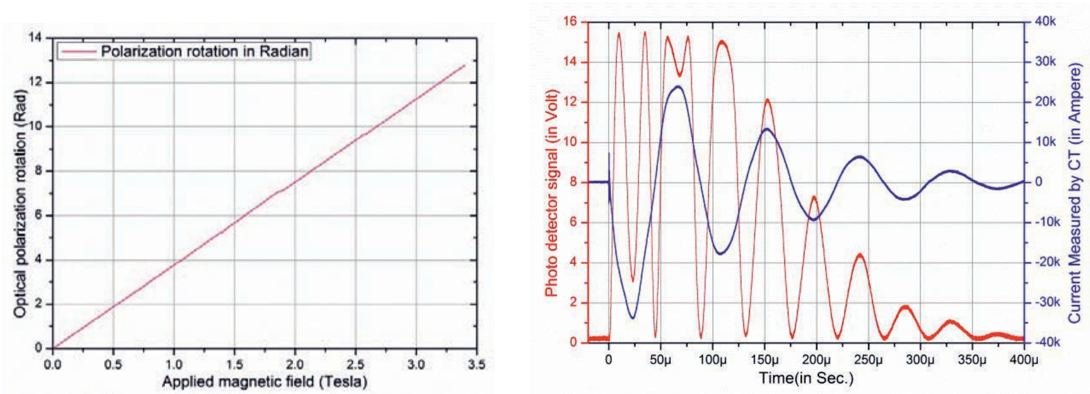

Figure 34.3. Calibration curve and typical signal (Red) with applied current (Blue) to the solenoid.[1]

Figure 34.3 shows typical photo-detector signal recorded on oscilloscope for time varying magnetic field, from the signal actual θ(t) has been found by counting number of half fringe and multiplying it by 90 deg. and adding fraction fringe by using $\sin^{-1}$ formula. Applied magnetic field (B(t)) can be computed using Eq. (34.1).

$$\theta(t) = 90 \times \left\{ N(t) + \frac{2}{\pi} Sin^{-1} \sqrt{V(t)/V_0} \right\} \text{ (Even no. of half fringe)} \tag{34.6}$$

$$\theta(t) = 90 \times \left\{ N(t) + 1 - \frac{2}{\pi} Sin^{-1} \sqrt{V(t)/V_0} \right\} \text{ (Odd no. of half fringe)} \tag{34.7}$$

34.3. Applications

The developed portable, cost effective and simplified high magnetic field measurement probe has been deployed for B-field measurement in various pulsed power experiments like electromagnetic compression welding system, electromagnetic expansion welding system etc. A pulsed magnetic field reaching up to 53 Tesla has been measured successfully with this probe.

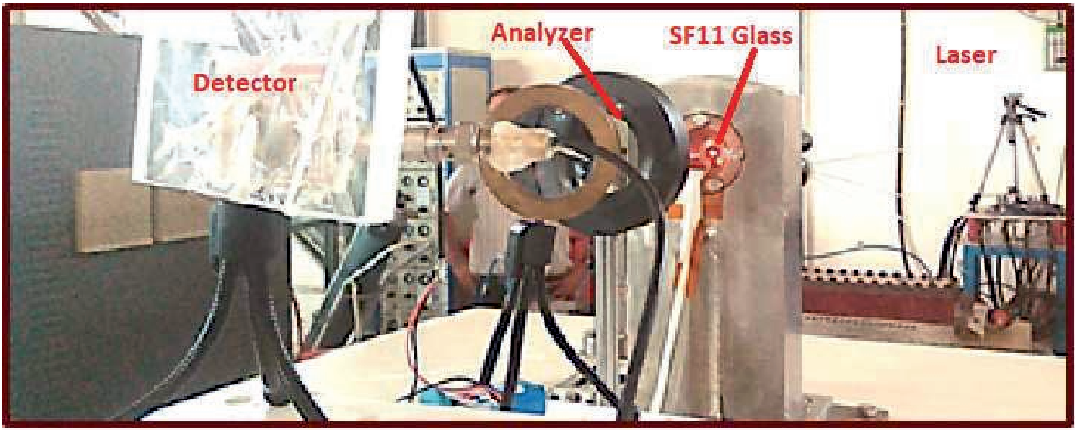

Figure 34.4. Magnetic field measurement in single turn coil. (B~50 T).

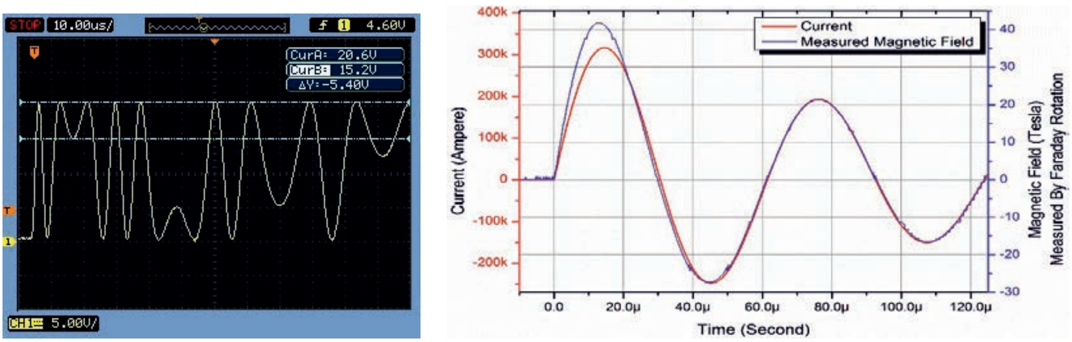

Figure 34.5. Typical detector signal for pulsed B-field measurement (left) and time resolved B field data with current waveform (right).

34.4. Summary

A compact high magnetic field measurement probe using Faraday rotation has been designed, developed, tested at different magnitudes of the magnetic field and deployed in various high field measurement. In the design we have tried to simplify every component of the system and we have intentionally chosen commercially available low cost items, so that overall cost of the whole system reduces without compromising accuracy, sensitivity and reliability. In Faraday rotation based measurement system, as we are measuring integral of rotation of plain polarized light due to interaction of magnetic field over some length, and for computation we are ignoring variation of magnetic field, result may be erroneous for magnetic field measurement on small coil. This integral error can be avoided by careful choice of sensor length and material with larger Verdet constant without losing sensitivity. Band width of the system can be improved by using high bandwidth photo detector.

References

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