

Magnetic Field Sensor Based on Corroded Multi-mode Fiber Structure

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Abstract. Magnetic field detection plays a vital role in various applications, including measuring the strength of the Earth's magnetic field, detecting magnetic anomalies with different characteristics, and military applications such as submarine detection. This paper demonstrates an optical structure which utilizes the single and multimode fiber with magnetic fluid to detect magnetic field. To enhance its sensitivity in detecting magnetic field strength, the multimode fiber (SMS) structure is corroded with hydrochloric acid (HCl). Within the SMS sensor, a short segment of multimode fiber as the sensing element, leading to the occurrence of multimode interference along the fiber. The sensor successfully detects magnetic field strengths ranging from 1.5 mT to 7.4 mT. The achieved sensitivities for magnetic field strength are -795.2 pm/mT and -327.9 pm/mT, corresponding to the length of MMF at 39mm and 45mm, respectively. The linear fitting coefficients R^2 achieved for the 39mm and 45mm MMF length are 0.8884 and 0.9814, respectively.

Keywords: Magnetic field detection, multimode interference, SMS structure.

1 Introduction

Optical fibers also play a crucial role in various sensing applications. By incorporating different sensing mechanisms into the fiber structure, optical fiber sensors can detect and measure physical parameters such as temperature, pressure, strain, vibration, and chemical composition. These sensors offer advantages such as high sensitivity, resistance to electromagnetic interruption, and the ability to monitor remote locations. In 2020, Deng et. al conducted a numerical analysis on the manufacture of bent modified plastic optical fibers (POF) for liquid level sensors [1]. The usage of the modified structure was to enhance the light transmission as well as the evanescent field from one POF to the other. Another study by Li et. al investigated the microfiber Fabry-Perot interferometer in the capillary using a polydimethylsiloxane (PDMS) as temperature detector [2]. Ding et. al demonstrated the effectiveness of the proposed sensor configuration for refractive index sensing using surface plasmon resonance [3].

The tapered coreless optical fiber structure exhibits distinct changes in the transmission spectra, which are highly responsive to variations in the refractive index of the medium. The wavelength interrogation sensitivity of the respective sensor with the range RI of 1.33-1.391 was recorded as 2278.4 nm/RIU.

Optical fiber sensors provide many advantages for electromagnetic detection. These sensors utilize optical fibers as the sensing element, which allows ability to convert electromagnetic signals into measurable changes in properties of light propagation. Many studies developing various sensing mechanisms, including the magneto-optic effect, electro-optic effect, and the Faraday effect. The use of magnetic fluid in optical fiber detector for magnetic field sensing was employed in Fiber Bragg Grating (FBG) [4], [5] and interferometers [6]. These sensors have demonstrated their magnetic field sensitivities. In addition, the long-period fiber grating (LPFG) [7] and MF-sealed MMF [8] have been investigated, showing high sensitivities to the magnetic field.

A work by Yi Huang et. al [9] investigated an intensity-modulated optical fiber sensor configuration that incorporates a magnetic fluid as the sensing element. The sensor utilizes a combination of magnetic fluid (MF) and multimode interference (MMI) to achieve favorable sensitivity measurement. The MF is a colloidal suspension comprising magnetic nanoparticles coated with surfactants, which engage with the magnetic field under measurement. Another similar work on an experimental investigation to measure temperature and magnetic field strength with the usage of the multimode fiber (MMF) and the long-period fiber grating (LPFG) sealed with MF (Miao et al., 2015). The LPG-MMF sensor exhibits distinct spectral responses to temperature and magnetic field changes.

In addition, Sun et. al designed a multi-function sensor using no-core fiber and elliptical-core spun fiber, arranged in cascade form within a fiber loop mirror [11]. These two fibers serve as the sensing elements, each exhibiting sensitivity to magnetic field and temperature variations, respectively. Another research on a magnetic field detector with a high sensitivity up to 4.08 nm/mT was conducted by Gu et. al. The designed sensor uses magnetic fluid as the cladding for a long-period fiber grating (LPFG) structure with dual peak resonances [7]. Another experiment conducted to increase the sensitivity of sensor is by immersing it under an acidic solution. Meanwhile, Wang et. al developed a multimodal structure as a magnetic field detector [12]. Hydrofluoric Acid (HF) was used in this experiment to produce air gap inside the fiber's cladding. The structure has been corroded by HF at the range of 0s to 1680 and obtained maximum sensitivity of -16.86 pm/Oe.

2 Methodology

2.1 Fabrication of Corroded SMS Magnetic Field Sensor

The sensor structure used for magnetic field sensor in this study is illustrated in Fig. 1. The process of constructing the sensor involves several steps. Initially, the cladding of

the optical fiber is stripped, and the fiber is cleaned with alcohol to remove impurities. The optical fiber is then cleaved using the Sumitomo Electricity Fiber Cleaver (FC-6RM-C). The SMS sensor is utilizing a short segment of multimode (MMF), connecting in between the single-mode fiber (SMF). The sensor is then subjected to corrosion using 30ml of 37% hydrochloric acid (HCl) for a duration ranging from 900s to 1020s. After the corrosion process, the sensor is dried for 120s. The corroded SMS structure is carefully examined using a fusion splicer. To protect against leakage or evaporation of the magnetic fluid (MF), the sensor probe of the corroded SMS is inserted into a 2mm diameter capillary silicone tube, and the MF is injected using a syringe. Epoxy glue is applied to both ends of the capillary tube to secure and seal it. The sensor probe remains positioned in the center of the capillary tube and should not be bent or twisted. The corroded SMS structure is then immersed in oil soluble Fe₃O₄. The magnetic fluid used in the experiment is manufactured by Ferrotech Corporation and has a viscosity of 12cP.

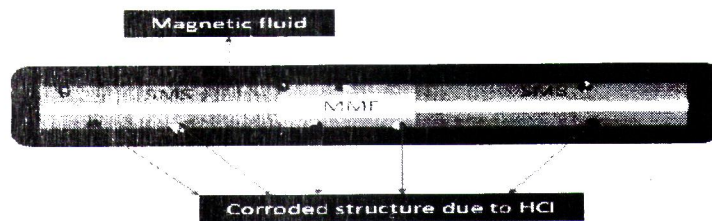


Fig. 1. Corroded SMS Magnetic Field Sensor

2.2 Fabrication of Corroded SMS Sensor

To establish the magnetic field for the experiment, a setup involving two electromagnets is utilized. The laboratory has an 800N force DC 12V ultrathin sucked electric lifting hold magnet electromagnet, which is accessible and suitable for generating the desired magnetic field strength. A DC power supply is employed to provide the necessary current for the electromagnets. By adjusting the voltage of the DC power source, the strength of the electromagnets can be modified accordingly. A Tesla meter (MG-3002) from Lutron Instrument was employed for measuring the magnetic field intensity. The setup for the magnetic field generator, including the electromagnets and the Tesla Meter, is depicted in Fig. 2.

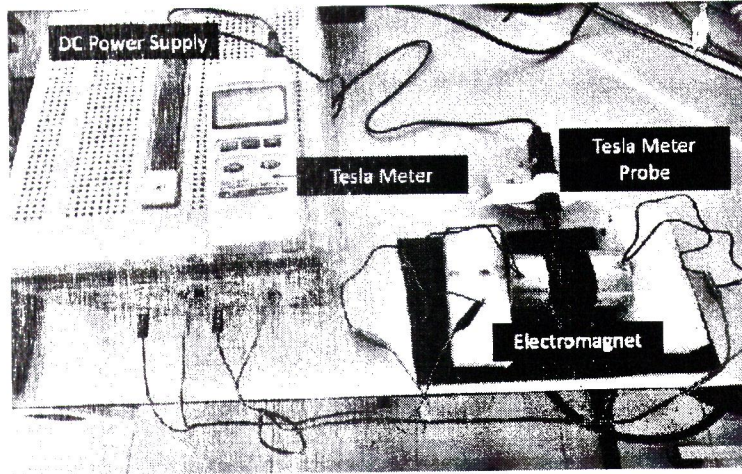


Fig. 2. Laboratory Setup for Measurement of Magnetic Field Strength

Fig. 3 illustrates the placement of sensor probe, positioned between two electromagnet poles, aiming to investigate magnetic field sensing. The sensor probe is optically coupled with light from the broadband source with a C-band wavelength. The other end of the sensor probe is connected to the AQ6370C optical spectrum analyzer (OSA) to observe the transmission spectra of the optical sensor at the regulated temperature of 25°C. When the magnetic field increases, the refractive index of fluid changes, causing in a dip and peak wavelength shift in the transmission spectra. However, the overall pattern of the transmission spectra remains unchanged. On the other hand, for the corroded SMS structure, the effective refractive index (RI) shifts around the corroded zone when a magnetic field is supplied in a other direction from the fiber axis. This shift affects the pattern of the interference dip.

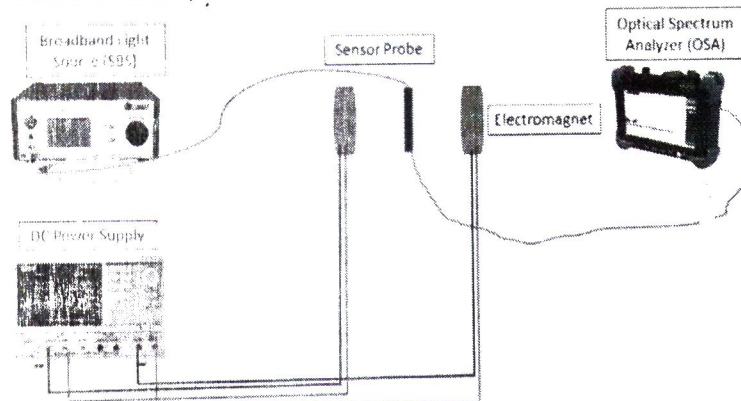


Fig. 3. Experimental Laboratory Setup for Magnetic Field Sensing

3 Results & Discussion

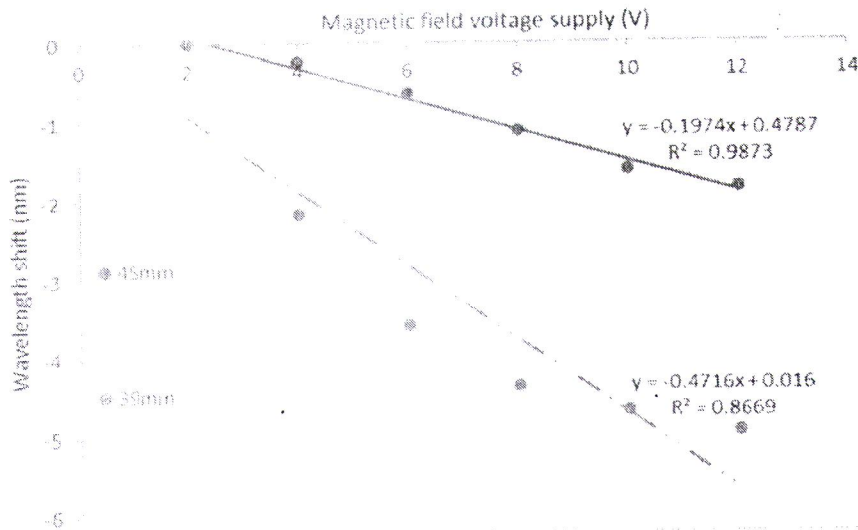


Fig. 4. Wavelength shift as a function of the transmission spectrum for corroded-MF SMS structure supplied at different voltages

The plot in Fig. 4 illustrates the relationship between the voltage supply of the electromagnets and the relative the wavelength shift of dip. The figure demonstrates a close to linear correlation between the wavelength shift of the dip and the applied voltage. By conducting linear fitting analysis on the experimental data, sensitivities of -471.6 pm/V and -197.4 pm/V were obtained for the length of the MMF sensing element at 39mm and 45mm, respectively. The linear fitting coefficient (R-squared) achieved for the 39mm and 45mm MMF lengths were 0.8669 and 0.9873, respectively.

Meanwhile in Figure 5, the plot displays the relative shift of the wavelength dip at distinct magnetic field intensity for both the 39mm and 45mm lengths of MMF. The sensitivity, defined as $d\lambda/dH$ (change in wavelength per unit change in magnetic field strength), indicates the wavelength shift of dip has linear correlation with the magnetic field intensity. This behavior is attributed to the increase in the refractive index (RI) of the magnetic fluid (MF) surrounding the corroded SMS structure, which correlates with higher magnetic field strengths. Based on the figure, the calculated sensitivities for the 39mm and 45mm lengths of MMF are -795.2 pm/mT and -327.9 pm/mT , respectively. These values represent the change in wavelength per unit change in magnetic field intensity. Additionally, the linear fitting coefficients are reported as 0.8884 for the 39mm MMF and 0.9814 for the 45mm MMF.

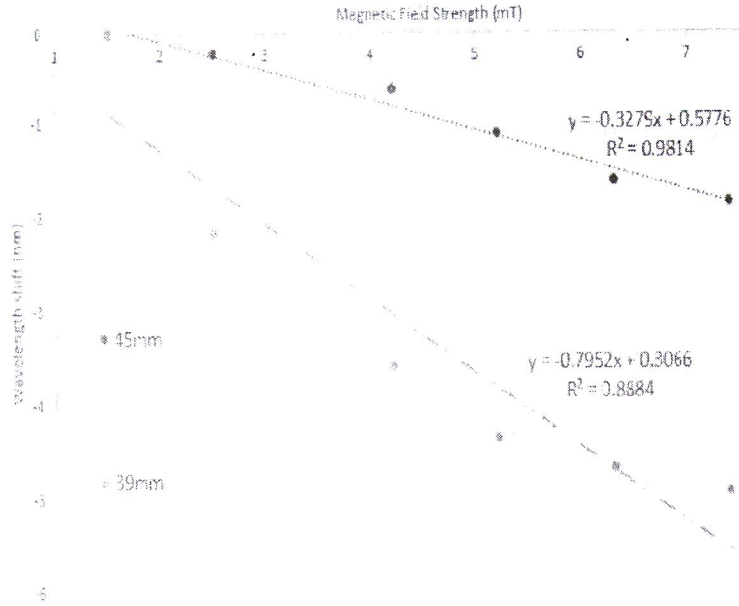


Fig. 5. Wavelength shift as a function of the transmission spectrum for corroded-MMF SMS structure supplied at different magnetic field strength

Comparing the obtained data, it is evident that the 39mm length of MMF exhibits high sensitivity in both cases (-471.6 pm/V and -795.2 pm/mT). However, the 45mm length of MMF achieves a higher R-squared value of 0.9873 for the supply voltage of the electromagnet and 0.9814 for the magnetic field strength. Moreover, the transmission spectra of the 45mm length of MMF shows better performance with less noise compared to the 39mm length. The 45mm MMF exhibits a smoother wavelength shift when subjected to varying magnetic field intensities. In light of these findings, it can be inferred that the utilization of the 45mm length of MMF as a sensing element is appropriate. This choice offers desirable characteristics such as enhanced sensitivity and a higher degree of consistency and reliability in the intensity of dips observed in the measured signals

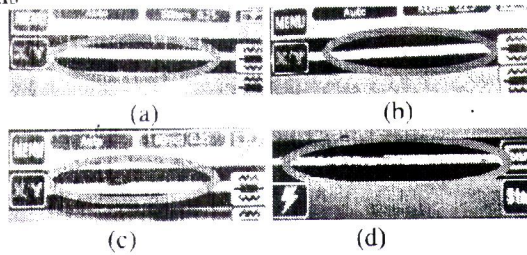


Fig. 6. The SMS sensor with 45mm MMF structure corroded by HCl for (a) 0s, (b) 900s, (c) 960s and (d) 1020s

In Fig. 6 (a)-(d), the evolution of the SMS structure's corrosion is depicted at different time intervals: 0s, 900s, 960s, and 1020s. These images are captured using a fusion splicer. The circle below each image illustrates the change in the air gap within the cladding as the corrosion time increases. It can be observed that with the passage of time, the corrosion process leads to an increase in the air gap formed within the cladding. During this exposure time, the corrosive nature of HCl interacts with the fiber's cladding, causing changes and effects such as the creation of an air gap within the cladding.

4 Conclusion

The corroded SMS magnetic field sensor has demonstrated the capability to detect low magnetic field strengths. In the experiment, two variations of the sensor were constructed using SMS with 39mm and 45mm lengths of MMF. To improve the sensor's sensitivity, an HCl corrosion approach was employed. The sensitivities of the magnetic field detector, based on the magnetic field strength, were found to be -795.2 pm/mT for the 39mm MMF and -327.9 pm/mT for the 45mm MMF. These sensitivity values represent the change in wavelength per unit change in magnetic field strength. For the 39mm MMF, the linear fitting coefficient achieved was 0.8884, while for the 45mm MMF, it was 0.9814, which suggest that as the magnetic field strength changes, there is a proportional shift in the dip wavelength. In summary, the corroded SMS magnetic field sensor exhibited the ability to detect low magnetic field intensities. The sensitivity values and linear fitting coefficients achieved for the 39mm and 45mm MMF variations indicate their respective performance in sensing magnetic fields.

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