High performance tunable fiber-optic current sensor based on Faraday rotation in toroidal sensing coil

Somarpita Pradhan*[a], Ali Masoudi[a], Gilberto Brambilla[a]
[a]Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

ABSTRACT

A high performance fiber-optic current sensor (FOCS) based on Faraday rotation in a toroidal sensing coil is proposed and demonstrated. The sensor performance has been improved by forming a toroidal sensing head to experience large magnetomotive force for a very small signal of electric current. In order to improve the sensor performance even further, the effective optical path length is increased by making a fiber coil, and the operating wavelength has been shifted to shorter wavelength (1064 nm) compared to the conventional telecom wavelengths (1550 nm) to benefit from a higher value of Verdet constant in conventional single mode fibers. Several toroid-core structures have been simulated using finite element analysis (COMSOL Multiphysics) to obtain enhanced sensitivity. The FOCS design includes an optimized 3D printed core structure along with toroidal windings and fiber loop inside it. Faraday rotator mirror (FRM) compensates for the birefringence along the sensing arm of the setup, while laser amplitude modulation is implemented using an electro-optic modulator (EOM) to enhance the signal to noise ratio at a particular modulated frequency. The developed FOCS set-up with four layers of copper wire windings in toroidal sensing head configuration is capable of detecting low currents of the order of 50 mA within a tested dynamic range of operation 0-10A. Detection of even lower order current (as low as several mA) could be achieved by tuning the design of sensing head.

Keywords: Faraday Rotation, Verdet Constant, Magneto-Optic Effect, Current Sensor, Fiber Optic Sensor.

1. INTRODUCTION

Measurement of electric current by means of optical methods is of great interest due to many desirable advantages[1-8]. Among developed optical current sensors (OCS's), one class is based on the principle of Faraday Effect[5-8] which deploys sensing element in the form of either a continuous length of optical fiber[9-15] or a bulk optical glass[16-19]. OCS utilizing optical fibers as sensing element offers possibility of remote sensing, immunity to electromagnetic interference and implements compact design with fast response time, hence attracted a lot of attentions during last decades. FOCS, which employs Faraday Effect to measure electric current, is governed by the basic principle of measuring rotation (θ) of the polarization azimuth in presence of magnetic field (B) in the direction of light propagation generating from current flow (I) in a conductor. The Faraday rotation angle can be expressed as[20],

$$\theta = V\int B \cdot dl = \mu VNI \tag{1}$$

Here N is the turns in the fiber coiled around the conductor, l represents the interaction length between the light and magnetic field, μ is the magnetic permeability ($\mu = 4\pi \times 10\text{-}7$ H/m for free space) and V is the temperature and wavelength dependent material parameter known as the Verdet constant which determines the level of polarization rotation. The Verdet constant is a material property which, in conventional telecom fibers, has a value of ~ 0.54 rad/T.m at conventional telecom wavelengths (λ~1.55μm)[21].

To design an FOCS with mA order current sensing capability, a significant rotation angle at a given electric current (I) needs to be produced. Several approaches have been used to design FOCSs with high sensitivity but most of them have significant weaknesses in terms of durability, ease of fabrication, stable response and simple detection technique. In our most recent work, we developed a current sensor with improved sensitivity by considering enhanced effect of the governing parameters (V, B or l) responsible for Faraday rotation.

*S.Pradhan@soton.ac.uk

The FOCS design includes an optimized toroidal sensing head to experience a large magnetomotive force (B) for a very small signal of electric current. In order to improve the sensor performance even further, the effective optical path length (l) is increased by making a fiber coil, and the operating wavelength has been shifted to shorter wavelength (1064 nm) compared to the conventional telecom wavelengths (1550 nm) to benefit from a higher value of Verdet constant (V) in conventional single mode fibers.

2. OPTIMIZATION AND FABRICATION OF TOROIDAL SENSING HEAD

2.1 Optimization of toroid design

The most effective way to enhance Faraday rotation for small electric current signal is to concentrate magnetic flux by forming a toroid configuration. The expression for magnetic flux density (B) inside a toroid filled with a material having permittivity μ ($= \mu_o \mu_r$), radius r and total number of turns (N) is,

$$B = \frac{\mu_0 \mu_r N I}{2\pi r} \tag{2}$$

Here, the permittivity of vacuum is represented by μ_o. I denotes the current flowing through the conductor wire.

Several toroid-core structures have been simulated using finite element analysis (COMSOL Multiphysics) to optimize the toroid configuration in terms of air-groove size, toroid dimension, number of current carrying copper wire turns and magnetic flux distribution for toroid-core geometry with inside groove has been investigated. Figure 1 represents a 2D cross section of toroid geometry (figure 1(left)) used for simulation and generated magnetic flux profile (figure 1(middle)) inside the toroid for a 10A magnitude of current flowing through the copper windings.

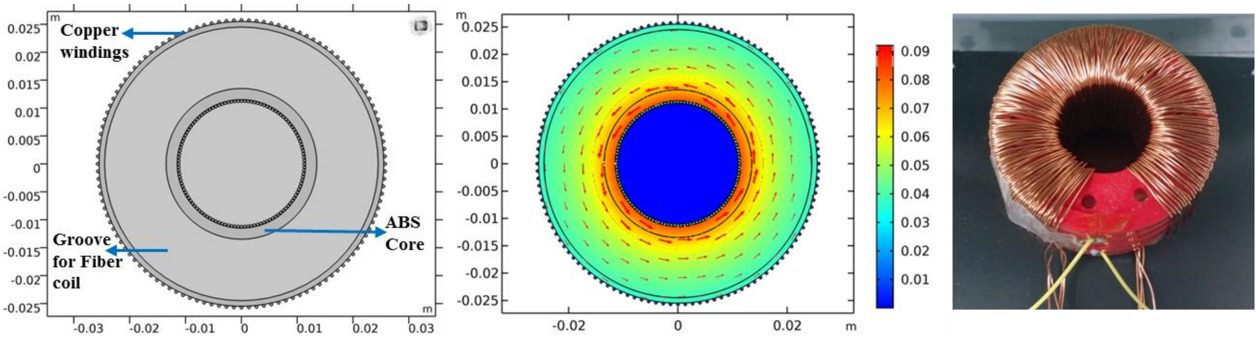

Figure 1. Geometry of the simulated toroidal core in 2D (left), COMSOL simulated magnetic flux density profile for toroidal core (middle) and photograph of fabricated toroidal fiber coil sensing probe prepared for FOCS (right).

The figure 1(middle) depicts that strength of magnetic flux in the air-groove decreases at the outer regime of the toroid structure which means the average magnetic flux density will reduce significantly for larger dimension of toroid. On the contrary, it will allow accommodating more length of sensing fiber as the air-groove size increases which improves the sensor sensitivity by modifying effective length of interaction (l). Therefore, it is an optimization of these parameters to achieve a final toroid structure and restricted by the permissible bend radius of the sensing fiber used in the air groove.

2.2 Fabrication of toroidal sensing coil

The optimized core structure parameters obtained from COMSOL simulation was then designed in Autodesk Fusion 360 platform and fabricated using a 3D printer (Ultimaker 3 Extended). ABS (Acrylonitrile butadiene styrene), a thermoplastic polymer, has been chosen as core material for toroid core as it is one of the most heat resistant materials reported in literature and compatible with 3D printing (Printing Temperature 250°C) facility[22,23]. After careful incorporation of sensing fiber coil (~150m) inside the air-groove of 3D printed ABS-core, winding of copper wires in multiple layers (4 numbers) around the ABS core has been performed to obtain toroidal structure. In our experiment, we used a toroidal sensing coil (shown in figure 1(right)) with outer diameter ~ 45mm and 54 numbers of turns in each copper winding layers connected in series.

3. SENSING EXPERIMENT AND RESULTS

3.1 Current sensing experimental set-up

As Verdet constant is wavelength dependent, sensing experiment was performed at 1064 nm wavelength to utilize the benefit of higher Verdet constant (~1.12 rad/T.m) of sensing fibers (1060 XP) at this specific wavelength compared to the conventional telecom wavelengths (at 1550 nm, V=0.54 rad/T.m). The FOCS design includes a polarisation maintaining (PM) circulator and a polarisation controller (PC) which operate in conjugation with a Faraday rotator mirror (FRM) to compensate for the birefringence in the fiber-coil and optimize the detected signal.

In the developed configuration, light is launched from the 1064 nm laser diode into the polarisation maintaining circulator and is divided into two components of orthogonal polarization. Since the light in each axis after 90º reflection via the Faraday rotator mirror returns via the orthogonal axis, all the effects associated to the linear birefringence in the sensing fiber loop were cancelled.

An electro-optic modulator (EOM) has been used to modulate the laser amplitude to enhance the signal to noise ratio at a particular frequency (1 MHz). Set-up used for this purpose is schematically shown in figure 2.

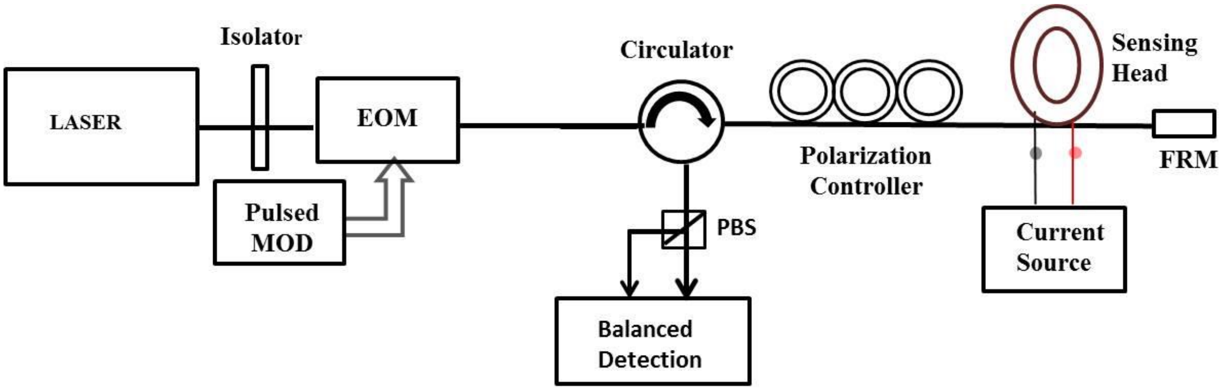

Figure 2. Schematic diagram of fiber-optic current sensing configuration using toroidal fiber coil as sensing probe.

3.2 Result and discussion

Current flowing through the toroid coil generates magnetic field in the direction of light propagation through optical fiber coil (as shown in COMSOL simulated magnetic flux density plot (figure 1)) and causes rotation of polarization azimuth of the propagating light. The rotation of the polarisation azimuth due to Faraday Effect is detected by measuring relative shift in the output signal voltage (V_R) amplitude recorded using balanced detection.

$$V_R = \sqrt{\frac{V_i - V_0}{V_0}} \tag{3}$$

Here V_0 represents the output voltage at zero current and V_i is the output voltage at specific coil current (I).

Toroidal fiber coil probe with 4 layers of copper wires arranged in series connection showed noteworthy sensitivity with stable response. The developed configuration is capable of detecting small current of the order of 50mA within a large dynamic range of operation (0-10A). Estimated output signal amplitude shift with applied current is shown in figure 3 which shows an almost linear response.

It is also evident from the plot that the performance of toroidal sensing coil improved due to multiple number of copper windings compared to the single layer. Further, addition of copper layers would enhance the sensitivity but with a limitation of reduced dynamic range of current sensing. Detection of current of the order of mA could be achieved by adding multiple numbers of copper winding layers and choosing a right combination of series/parallel connection.

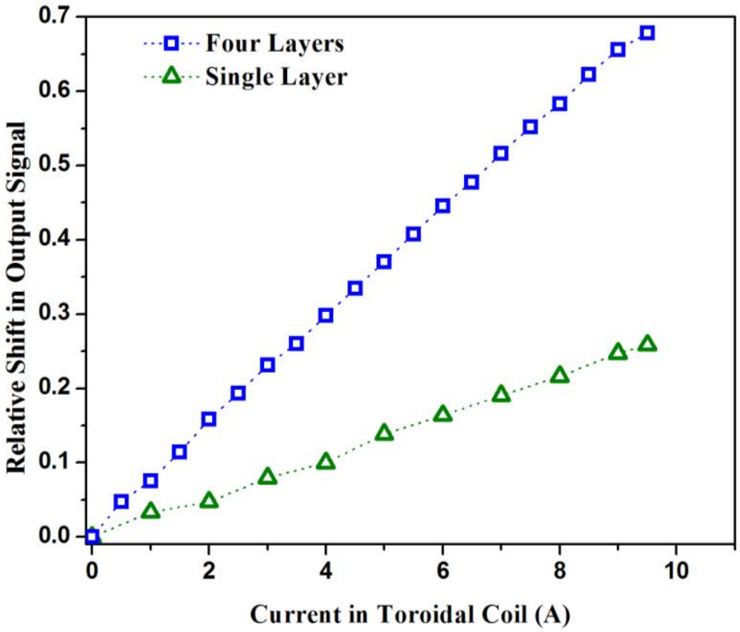

Figure 3. Sensor response: Relative shift in output signal voltage as a function of applied current in toroidal sensing coil.

4. CONCLUSION

In this work, we have demonstrated a current sensing configuration based on our in house fabricated toroidal sensing coil which is capable of sensing small current of the order of 50 mA (0-10A). The sensor performance presented here attributes to only one specific set of series connection of the copper windings in the sensing coil. The design opens possibilities for even smaller order current detection (~mA) with variable dynamic range of operation by choosing different series/parallel combinations of connections between multiple copper winding layers. Sensitivity can also be tuned by modifying toroid-core geometry depending on the desired application. With its tunable nature of performance and compact design, the FOCS is suitable for most of the weak current sensing applications.

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