# Temperature-Monitored Fibre Optic Current Sensor Using Channelled-Spectrum Analysis

P. Robalinho, M. Melo, O. Frazão, and A. B. Lobo Ribeiro

***Abstract*— The fibre optic current sensor demonstrated here uses the intrinsic temperature and wavelength dependence of the Verdet constant of a terbium gallium garnet (TGG) magneto-optic material and the two micro-optic linear polarizers attached, to simultaneously extract the values of temperature and the optical Faraday rotation (induced by the presence of the magnetic field due an electric current on a conductor) without any extra optical component attached to the optical sensor head. The simultaneous measurement is achieved by illuminating the sensor head with a broadband optical source and by careful signal processing of the originated channelled-spectrum, compensate the sensor's temperature dependence.**

***Index Terms*— Current sensor, fibre optic, magneto-optic, channelled-spectrum, TGG.**

## I. Introduction

GENERALLY, an optical current sensor (OCS) is a polarimetric device that employs the Faraday effect in a magneto-optical material as the sensing principle [1]. The electric current value to be measured is derived from the polarization rotation induced by the external magnetic field acting in the optical material. In most cases, the optical materials used are glasses (e.g., FR5, SF2, or Flint glasses), paramagnetic materials (e.g., TGG-terbium gallium garnet), diamagnetic materials (e.g., BSO-bismuth silicate), ferromagnetic or ferrimagnetic materials (e.g., YIG-yttrium iron garnet) and also rare-earth-doped silica optical fibres. These materials are strongly influenced by the temperature variations which will have a great impact on the sensor's sensitivity. The polarization rotation is then a function of the external magnetic field strength, the physical length and the Verdet constant of the magneto-optical material used [1]. Some of these materials have high Verdet constant (such as ferromagnetic and ferrimagnetic materials) and some have a low Verdet constant (such as diamagnetic and paramagnetic), but nevertheless, this parameter varies both with wavelength and temperature. In the case of the paramagnetic material used on this work, that is, Terbium Gallium Garnet (TGG) this temperature-wavelength dependence is well known [2], [3], [4].

Due to the reason that the Verdet constant of this type of magneto-optic material is temperature dependent, its temperature value can be directly measured using some kind of temperature sensing device and by digital look-up table subtracted to the detected signal [5]. Other authors have incorporated within their TGG crystal head, a temperature-dependent birefringent wave-plate and a Wollaston prism to separate two complementary optical signals, adding this way, an extra complexity and cost to the sensor head [6]. Also, some others have used dual-wavelength configuration to improve this temperature dependence of the magneto-optic device [7].

The proposed optical sensor of this work makes use of this intrinsic temperature-wavelength dependence, both on the TGG crystal and on the micro-optic linear polarizers attached to it, and by illuminating the assembled sensor head with a broadband optical source and with a dedicated software algorithm to analyse the originated channelled-spectrum, it's possible to compensate the temperature fluctuations in the electric current (or magnetic field) measurement without any extra optical component attached to the sensor head.

## II. Experimental

The optical sensor head is represented schematically in Fig.1, and it consists of a two GRIN collimating lenses, attached to each a ~1 mm thick micro-optic linear polarizers (the principal axis of the output polarizer is oriented at 45° with respect to input polarizer), and between the two, a magneto-optic rod crystal made of TGG material with a physical length of 20.5 *mm*. The fibre optic packaged sensor head have a 4 mm diameter and total length of 50 *mm*, pigtailed with HI1060 single mode fibre. The Verdet constant is about −13.8 *rad/T· m* (that is, −744.9 *deg/T· m*) at 1550 nm wavelength and room temperature [2], [3]. Fig. 2 shows a photo of the assembled fibre optic device. The sensor was illuminated by an erbium-doped broadband fibre optic source (BBS) emitting 100 *mW* output power, centred at 1560 nm wavelength and spectral bandwidth of 90 *nm*, with active temperature control. The output optical signal from the sensor is detected by an optical spectrum analyser (OSA) instrument with a resolution of 0.01 *nm* and processed with a dedicated software algorithm written in Python language. To induce a magnetic field longitudinal to the sensor head, a solenoid was used and its driving electric current controlled from 0 to 2 *A* (giving an equivalent setup arrangement of an electric conductor distanced by 10 *mm* from the sensor head placed perpendicularly to this conductor, and where its electric current

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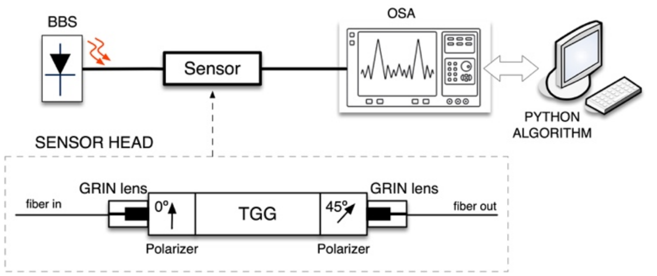


Fig. 1. Proposed sensing system, with detailed schematic design of the sensor head.

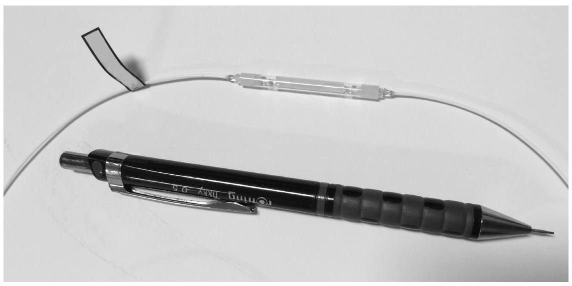

Fig. 2. Photo of the assembled fibre optic sensor (pencil just for dimensions comparison).

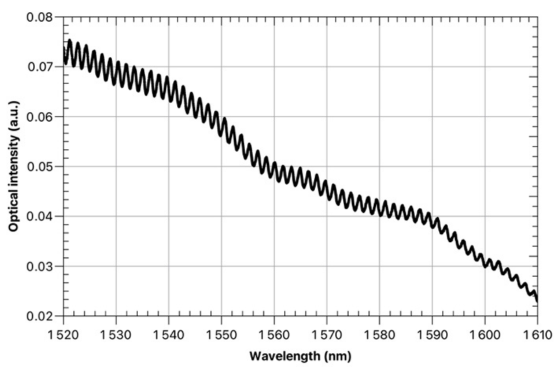


Fig. 3. Detected channelled-spectrum from the sensor head.

varies from 0 to 1700 $A$). The temperature of the sensor head was controlled by an in-house designed current controlled mini-oven that varies from +25°C to + 60°C.

## III. Results and Discussion

Fig. 3 shows the detected optical channelled-spectrum from the sensor at room temperature. Using an in-house developed Python algorithm, it's possible to analyse simultaneously the intensity and the interferometric spectral signatures from this channelled-spectrum. Fig. 4 shows these two spectral signatures separately.

The free spectral range (FSR) of the interferometric spectral signal is ∼1.6 *nm*, which agrees well with the physical thickness of the output linear polarizer that works also as a low finesse optical cavity to interferometrically measure the temperature of the sensor head.

By varying the electric current on the solenoid, the output optical intensity from the sensor head varies nearly linear (see fig.5), as expected due to the Faraday effect. The linear fitting slope ($\Delta O_{1550}/\Delta I = 5.14334 \times 10^{-6} A^{-1}$) agrees relatively well with the theoretical one ($\Delta O_{\text{teo}}/\Delta I = 5.67 \times 10^{-6}\ A^{-1}$), which can be calculated from the well-known electromagnetism relation for the magnetic field around the

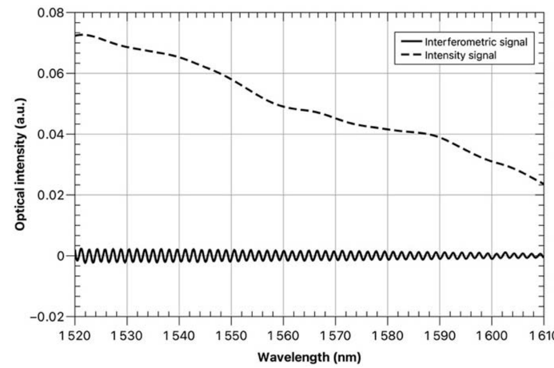


Fig. 4. Processed intensity and interferometric spectra.

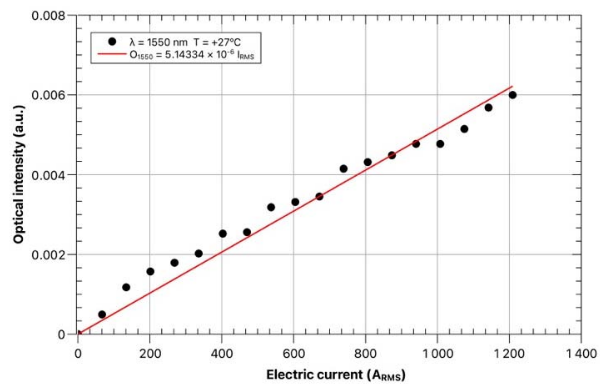


Fig. 5. Processed optical intensity response of the sensor.

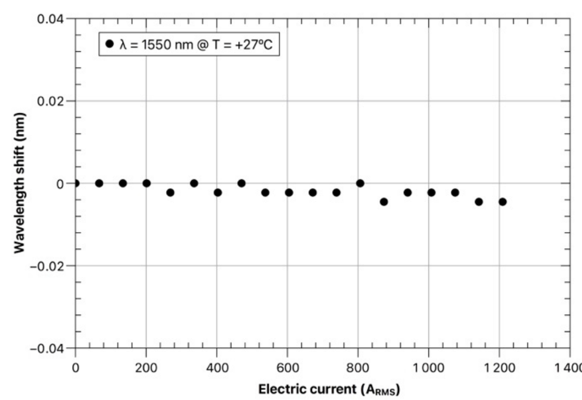


Fig. 6. Processed spectrum extreme wavelength shift of the interferometric response of the sensor with electric current variation on the solenoid.

electrical conductor with current $I$, that is, $B = \mu_0 I/(2\pi r)$ in combination with the optical Faraday rotation relation, that is, $\theta = BVL$, giving $\Delta O_{\text{teo}}/\Delta I = (\mu_0 VL)/(2\pi r)$. Thus, taking the 10 mm distance ($r$) of the sensor head from an electrical conductor, the length ($L$) of the TGG material of 20.5 mm and a Verdet constant of ∼13.8 *rad/T· m*, the theoretical value above can be calculated, resulting on a relative error of 9.3%.

From Fig.6, spectrum extremes positions variation measure, can see that the interferometric spectral signal is practically not affected by the variation of the induced magnetic field on the sensor head by the solenoid electric current. Which means that, this interferometric signal can provide, in principle, a real-time temperature measurement of the sensor head without being affect by the induced magnetic field, and thus be used to compensate electric current measurement obtained from the optical intensity signal. In order to confirm

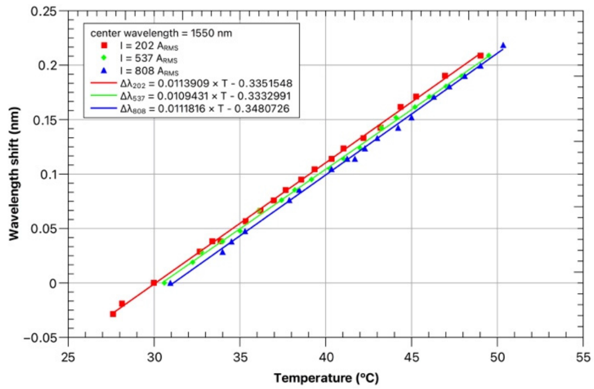


Fig. 7. Processed wavelength shift of the interferometric response of the sensor with temperature variation for different electric current settings.

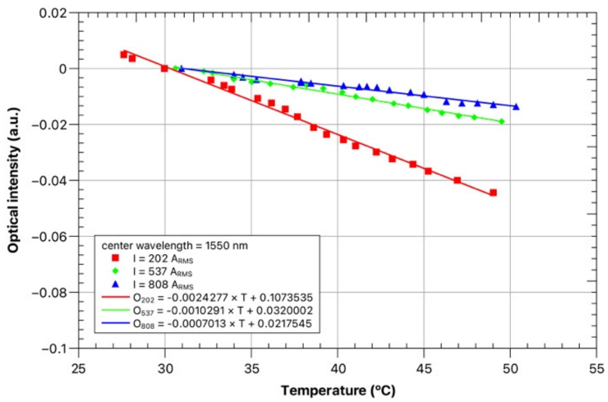


Fig. 8. Processed optical intensity response of the sensor with temperature variation for different electric current settings.

this hypothesis, we have measured the response of the of the interferometric signal from the channelled-spectrum with temperature variation of the sensor head, for different electrical current settings on the solenoid. Fig.7 shows precisely that. This interferometric signal is immune to the magnetic field (that is, the electric current on the solenoid), and can be used as an optical temperature sensor within the sensor head, giving a wavelength-to-temperature sensitivity ($\Delta\lambda/\Delta T$) of $\sim$11 $pm/$°C with a resolution of 0.01 $nm$ imposed by the processing scheme.

We have measured the response of the optical intensity signal with temperature variation of the sensor head, for different electrical current settings on the solenoid (that is, different magnetic fields). Fig.8 show these results and one can conclude that is necessary to have real-time information about the operational temperature of sensor head, which can be achieved by extracting the real-time temperature value from the interferometric spectral signal, in order to compensate this deviation on the optical intensity signal.

## IV. Conclusion

Using the simplest fibre optic configuration for an electric current sensor based on magneto-optic Faraday effect in combination with carefully spectral signal processing of the optical channelled-spectrum generated, it is possible to extract both the Faraday rotation information and the temperature variation of the sensor in real-time, without any extra optical or electric device attached to the sensor head.

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