COMPACT FIBER-OPTIC CURRENT SENSOR UTILIZING MULTIPLE MODES

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Abstract: In this paper, a simple and compact fiber-optic current sensor utilizing a standard telecom fiber is demonstrated. The sensor employs a Faraday effect introducing a circular birefringence, which is added to a birefringence induced by fiber coiling. The experiments revealed that multi-mode propagation of light with wavelength of 633 nm may exhibited much better sensitivity to the Faraday effect and is less harmed by the parasitic birefringence compared to single-mode beam with 1550 nm.

Keywords: Faraday effect, optical fiber sensors, current sensor, multi-mode.

1 INTRODUCTION

Sensing the electric current with optical fibers has attracted considerable attention due to specific advantages such as perfect electric insulation, safety, immunity to electromagnetic noise, low weight and possibility of long distance signal transmission. They are mostly based on magneto-optic Faraday effect consisting in rotating the polarization angle of the light propagating in parallel to the magnetic field induced by the current in a conductor. However, since the Faraday effect in standard silica fiber is weak, this kind of sensors has been conveniently utilized mainly for high current (≈kA) measurements. To enhance the sensitivity, the fiber is usually coiled into multiple wraps around the conductor. Both Sagnac interferometer-based and single-ended reflection-based configurations has been reported [2]. The Faraday rotation thus cumulates along the fiber length; however; there also acts a negative effect of birefringence. Note that apart from these polarization sensitive sensors there emerge also some other approaches to current measurement, e.g. those based on magnetic fluids and multi-mode interference [6], which are still under development.

This paper presents a compact coiled current sensor based on Faraday effect, where also the conductor is wound around the fiber coil into a toroidal shape. The interaction of the magnetic field with the optical wave is thus intensified by the factor of 10^6 compared to a single fiber and conductor loop. Based on this setup, both single-mode (SM) as well as multi-mode (MM) beam propagation is studied and the first results are reported.

2 THEORY

2.1 FARADAY EFFECT IN A COILED FIBER

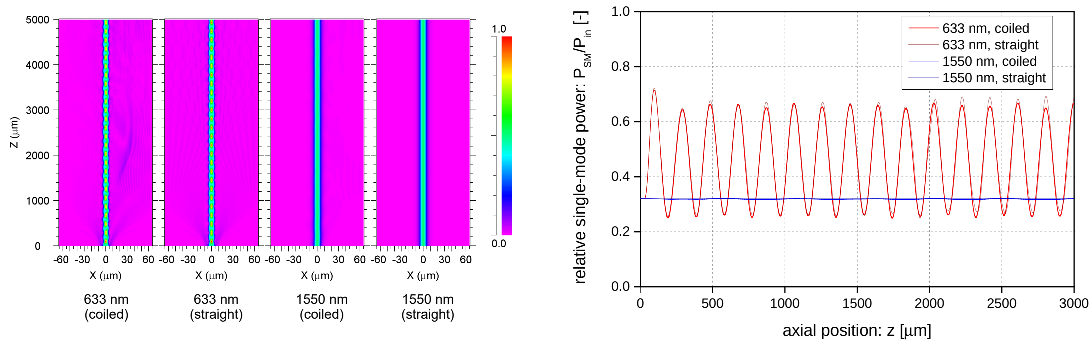
If an optical material is placed into a magnetic field $\vec{B}$, the Faraday effects causes introducing a small circular birefringence. Therefore, the plane of polarization of linearly polarized light will be rotated by angle

$$\theta = V \int_L \vec{B}\,\mathrm{d}\vec{l} \tag{1}$$

after passing the material, where L is the light path in the medium and V is Verdet constant expressing the magneto-optic properties of the material. This effect can also exhibit in optical fibers. It can be measured e.g. by launching a linearly polarized light into a fiber and placing a polarizer (analyzer) at the output [1]. Assuming the polarizer is in parallel with an initial polarization, the output power is in ideal case equal to $P_{\text{out}} = P_{\text{in}} \cos\theta$. However, in practical cases, the attempts to make such sensors compact and more sensitive yield in winding the fiber into multiple turns [2]. Although there are techniques to produce a fiber with very low bending loss, there is a more severe problem of bending-induced birefringence of SM fibers [4]. The resulting birefringence is thus a superposition of both bending and the Faraday effect. There exist techniques to decrease the sensitivity to the bending-induced birefringence such as annealing and twisting the fiber; nevertheless; for smaller coiling diameter the bending effect needs to be taken into account. The apparatus to the polarization state development in coiled SM fiber is established in [5]. It is based on four-parameters model, including a linear birefringence with defined angle and phase delay, polarization rotation and a random delay of light coupled between polarization modes. The first three parameters can effectively handled by placing a polarization controller before the fiber input, as demonstrated by [4]. However, such solution only enables to tune an optimal state of input polarization to maximize the Faraday effect, but not to reach its actual maximum. The reason is as follows: the bending-induced birefringence may change the initially linear polarization to circular. The Faraday effect then manifests as pure phase shift. However, the sign of the shift depends on the direction of polarization. Assuming the all states of polarization are in tightly coiled fiber distributed equally, the overall Faraday effect may be significantly weakened. In this case, we can define so-called effective Verdet constant as an overall magneto-optical parameter of coiled fiber. It was demonstrated e.g. by [1] that a fiber wound into 12-cm radius exhibited about 12-times smaller effective Verdet constant at 633 nm, compared to its intrinsic value.

2.2 Propagating of multiple modes

The known fact that the Verdet constant is wavelength-dependent can be approximately expressed as $V \approx \lambda^{-2}$ [4]. Therefore, most of fiber-optic current sensors tend to utilize shorter wavelengths, occurring in visible range, rather than in infrared telecom region. The spurious bending-induced birefringence discussed above can be also interpreted as an existence of two polarization modes, which are both affected by the Faraday effect. Nevertheless, similar effect is also present in case of multiple modes propagating through a MM fiber. In the experimental part we utilize a standard telecom SM fiber similar to SMF-28, having the cutoff wavelength $\lambda_c \leq 1260$ nm. The sensing performances were investigated for two wavelengths: $\lambda_1 = 633$ nm and $\lambda_2 = 1550$ nm. A beam propagation



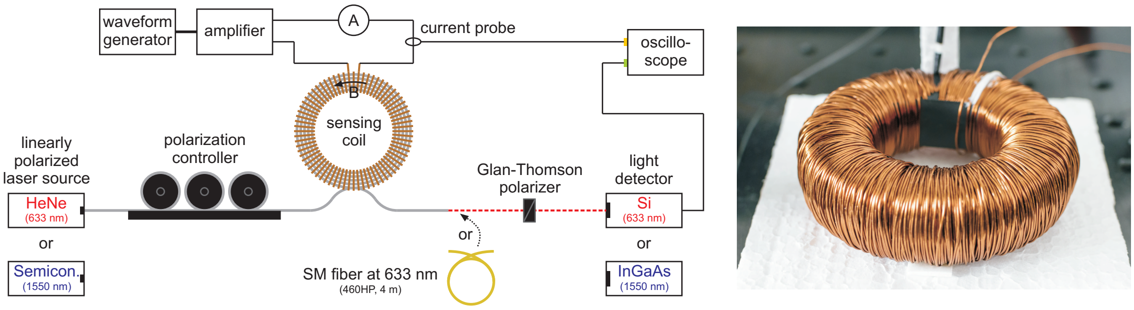
(a) **(b)**

Figure 1: Simulation of the beam propagation in SMF-28 fiber for λ_1 and λ_2 comparing the straight and coiled ($r = 25.5$ mm) fiber (a), and the corresponding SM (gaussian) power at particular position (b).

method was used to simulate a field distribution along the fiber for these wavelengths, where both straight fiber as well as fiber wound on a coil were compared (Fig. 1(a)). The considered coil radius was $r = 25.5$ mm, which corresponds to the experiment. Whereas the field has approximately gaussian distribution for λ_2, in case of λ_1 a pseudo-periodic multiple-mode interference may be observed. Nevertheless, due to different propagation constant β of each mode, they are propagating independently of each other [3] and also their rotation due to the Faraday effect will be slightly different. The aim of this study is to explore the behavior of compact-coiled fiber-optic current sensor where single as well as multiple modes are propagating through the fiber, since such a case have not been reported to our knowledge. In addition, by making the modes to interfere at the end, a very sensitive response could be obtained, as suggest the simulated SM power distributions in Fig. 1(b).

3 EXPERIMENTAL SETUP

The developed sensing coil consisted of $m = 1280$ wraps of standard telecom fiber, similar to SMF-28, wound in mean radius of $r = 25.5$ onto a 3D-printed plastic spool. Therefore, the total fiber length is estimated to 205 m. The varnished wire was then wound around the fiber coil to form a toroid having $n = 850$ wraps. The whole experimental setup is schematically shown in Fig. 2. Two different linearly polarized light sources were used providing wavelengths $\lambda_1 = 633$ nm (HeNe laser) and $\lambda_2 = 1550$ nm (semiconductor laser) coupled into an optical fiber. To handle the sensing coil input polarization state, a 3-paddle polarization controller (PC) was placed after the source. After passing the coil, the light was filtered by a wideband Glan-Thomson polarizer (GTP) with rotary mounting. Alternatively, an SM low-cutoff fiber (460HP, $\lambda_c \leq 450$ nm) having length of 4 m was inserted before the GTP to observe purely an SM power when λ_1 was used. The output power was turned to voltage by an Si detector for λ_1 and by an InGaAs detector for λ_1. The voltage was routed to a digital oscilloscope Agilent DSO7012B (CH1), together with the coil current sensed by the current probe (CH2). The current was also more accurately measured by the digital ammeter.



(a) (b)

Figure 2: Scheme of the experimental setup (a) and photo of the sensing coil (b). Two pairs of source and detector were used to test operation at λ_1 and λ_2. Alternatively, inserting a piece of low-cutoff fiber was tested to filter out higher modes at λ_1

4 RESULTS AND DISCUSSION

4.1 Observing the propagating modes

For the visible wavelength $\lambda_1 = 633$ nm it was possible to observe the output field after propagation through the fiber. In case of the used telecom fiber, the normalized frequency of $\nu = 5.7$ suggests there exist some higher-order modes. By pointing the output fiber onto a white plate instead of the GTP, the output field power distribution was projected and recorded by the camera. The field images for different PC settings are shown in Fig. 3(a–f). By comparing to the simulated modes shape in a MM fiber [3], the dominance of LP_{11} (b) and LP_{21} (a,c,e) modes may be noticed. These observations confirm the presence of multiple modes simulated by the beam propagation method. On the contrary, when the low-cutoff SM fiber is placed at the output, only the lowest LP_{01} mode is observed, as shown in Fig. 3(g–h) for minimal and maximal intensity reached by adjusting the PC.

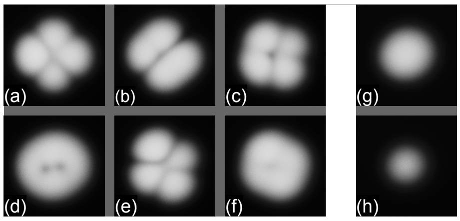


Figure 3: Observed field distribution at the end of telecom fiber (MM at λ_1) for different PC settings (a–f) and at the end of low-cutoff fiber (SM at λ_1) for minimal and maximal intensity achieved by the PC (g–h).

It was thus shown that the bending-induced birefringence (introduced by both PC and current sensing coil) can strongly affect the output field in case of MM propagation. On the other hand, there was not observed any significant change of the output image if a current was applied to the sensing coil. This suggests that whereas the polarization modes of each LP mode can interfere variously due to bending birefringence and thus completely diminish for particular PC settings, the Faraday effect induced by the current affects only the polarization, not the shape nor total power of the output beam.

4.2 CURRENT SENSING PERFORMANCES

To analyze the sensing performances, an AC current with $f = 120$ Hz was employed. Three different setup configurations were used: I(a) – λ_1 and MM propagation, I(b) – λ_1 and SM output filtration and II – λ_2 and SM propagation, whose results are summarized in Tab. 1. Firstly, the relative effective range $R_{\mathrm{AC/DC}} = P_{\mathrm{AC}}/P_{\mathrm{DC}}$ was measured as a ratio of detected AC (i.e. Faraday effect sensitive component) and DC (i.e. parasitic insensitive component) signal. The PC and GTP were always adjusted to reach the maximal possible AC signal. The measurement was performed for a constant current of $I = 0.2$ A_{rms}. Secondly, an effective Verdet constant was determined by comparing the current-induced polarization change to an equivalent rotation of the GTP. The PC was adjusted to reach a maximal sensitivity to Faraday effect before each measurement. The effective Verdet constant was calculated as $V_{\mathrm{ef}} = \theta/(\mu \cdot n \cdot m \cdot I)$, where I is measured current and $\mu \cong 4\pi \cdot 10^{-7}$ [N·A^{-2}] is permeability of the silica fiber. The comparison of V_{ef} to the intrinsic Verdet constant of unwound fiber V_{int} according to [4] (considering only SM propagation) is noted in Tab. 1. Finally, the dependence of the detector output AC voltage on the input current for the configuration I(a) was measured and is shown in Fig. 4. A maximal AC output signal was achieved by an optimal PC and GTP settings. Whereas for small currents the sensors characteristics are linear, a measurement in a wider range reflects the cosine relationship between the polarization angle and power after the GTP.

parameter	config. I(a) (λ_1, MM)	config. I(b) (λ_1, SM filt.)	config. II (λ_2, MM)
$R_{\mathrm{AC/DC}}$ [-]	0.635	0.176	0.127
V_{ef} [rad·T^{-1}·m^{-1}]	0.44	not measurable	0.030
V_{int} [rad·T^{-1}·m^{-1}]	3.25		0.52

Table 1: Major parameters of tested setup configurations.

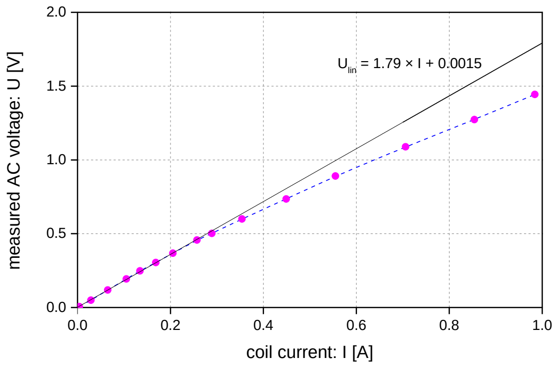


Figure 4: Dependence of the output AC voltage on the measured current for I(a) configuration and its ideal linear approximation.

5 CONCLUSION

In this paper, the Faraday effect inside a compact fiber coil was measured for MM as well as SM propagation. Whereas the bending birefringence decreased its sensitivity significantly in case of single mode with a wavelength of 1550 nm, the light having 633 nm wavelength propagating in several modes exhibited very good performances assuming proper input polarization setting. On the other hand, the SM filtration by the low-cutoff fiber brought only slightly improved performances; nevertheless; it revealed an instable behavior due to multiple-modes interference for some input polarizations. Therefore, the MM operation at 633 nm proved as the best option for the developed sensor.

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