Birefringence Treatment of Non-ideal Optical Microfiber Coils for Continuous Faraday Rotation

G. Y. Chen, G. Brambilla and T. P. Newson

A flexible technique to periodically perturb the evolution of differential phase in birefringent optical microfiber is proposed. This conceptual demonstration offers a simple yet effective solution to rectify non-ideal microfiber coil sensor heads for high-performance current sensing.

Introduction: The rise of optical microfiber technology [1] has opened up a new lineage of current sensing. Optical current sensors employing optical microfibers (OM) based on the Faraday Effect have shown their potential for ultra-fast current detection in ultra-small geometries [2–4]. However, as with conventional current sensors, the problem of birefringence [5,6] still persists. Spun optical microfiber was previously proposed and demonstrated [7]. It offered improvements in the current responsivity at the expense of increased fabrication time and resources. In this Letter, we propose a post-fabrication technique to achieve the same goal, but with considerably lower fabrication complexity.

Background theory: Optical microfiber coil (MC) based current sensors that exploit the Faraday Effect consist of an OM wrapped around the current-carrying conductor. The Faraday-induced rotation of the plane of polarized light is linearly proportional to the current flow. The change in the polarization azimuth is then translated into an intensity modulation that provides a measure of current. For the ideal case where there is no intrinsic birefringence in the MC, the angle of Faraday rotation (θ_{ideal}) is related to the Verdet constant (V) of the OM, the magnetic flux density (B), and the interaction length (L) of the OM. Assuming a uniform magnetic field, θ_{ideal} can be expressed in terms of the magnetic permeability of free-space (μ_0), the relative permeability of the OM (μ_r), the current flow (I), the radius of the fiber coil (r), and the number of OM turns (N):

$$\theta_{ideal} = V\int_0^L B\cdot \mathrm{d}l \approx VBL = \mu_0\mu_r NVI \tag{1}$$

where $B = \dfrac{\mu_0\mu_r I}{2\pi r}$ and $N = \dfrac{L}{2\pi r}$

In practice, it is common for macro-bending and polymer-packaging to induce linear birefringence in the fabricated MC. Owing to the varying differential phase, the transfer of power between the orthogonal axes of the birefringent OM is maximum after a quarter of the polarization beat length, and reduces to zero over half of the beat length. Hence, for MCs employing OMs longer than a quarter of the beat length, the only section in which interaction with the magnetic field will be measurable is the length remaining after subtracting an integer number of half beat lengths. The resulting Faraday rotation at after a propagation distance of L can be written as:

$$\theta_{non-ideal} = \int_0^L \tau\cos(\Delta\beta\cdot l)\mathrm{d}l = \frac{\tau}{\Delta\beta}\sin(\Delta\beta\cdot L) \tag{2}$$

where $\Delta\beta = 2\pi\Delta n/\lambda$ is the intrinsic linear birefringence, λ is the wavelength of light, and $\tau = VB = \mu_0\mu_r VI/(2\pi r)$ is the Faraday rotation per unit length.

Working Principle: By modifying the local birefringence at selective regions along the OM shown in Fig. 1, a gain of $\pm\pi$ in differential phase between the orthogonally polarized light in the axes of the birefringent OM can lift the device from a state that is on the brink of a reversal in Faraday rotation, to a state that is just emerging back into the same direction of Faraday rotation. Each region must be kept as short as possible to minimize the negative contribution to the total Faraday rotation, as the Faraday Effect is proportional to the interaction length. The required birefringence modulation (Δn) to achieve this effect for a given region length (L) is expressed by:

$$\Delta n = \frac{\lambda}{2L} \tag{3}$$

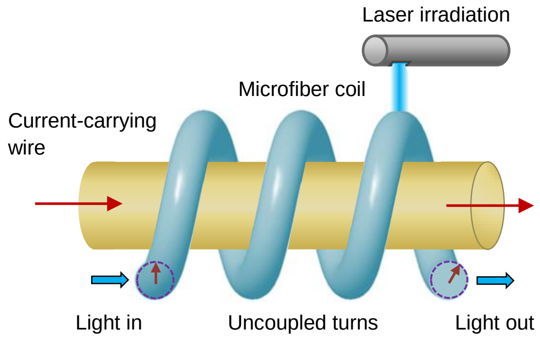

Fig. 1 *Illustration of the birefringence modulation technique at selective regions in the MC. Arrows in dashed-circles represent the rotation in polarization azimuth.*

Simulations and discussions: As shown in Fig. 2(b), the steady increase of differential phase along the length of the fiber is accompanied by the gradual reversal in Faraday efficiency in Fig. 2(c). At zero Faraday efficiency, Fig. 2(a) shows that a sharp rise in local birefringence that is sustained just long enough for the differential phase to grow by π, facilitating positive Faraday rotation once again in Fig. 2(d).

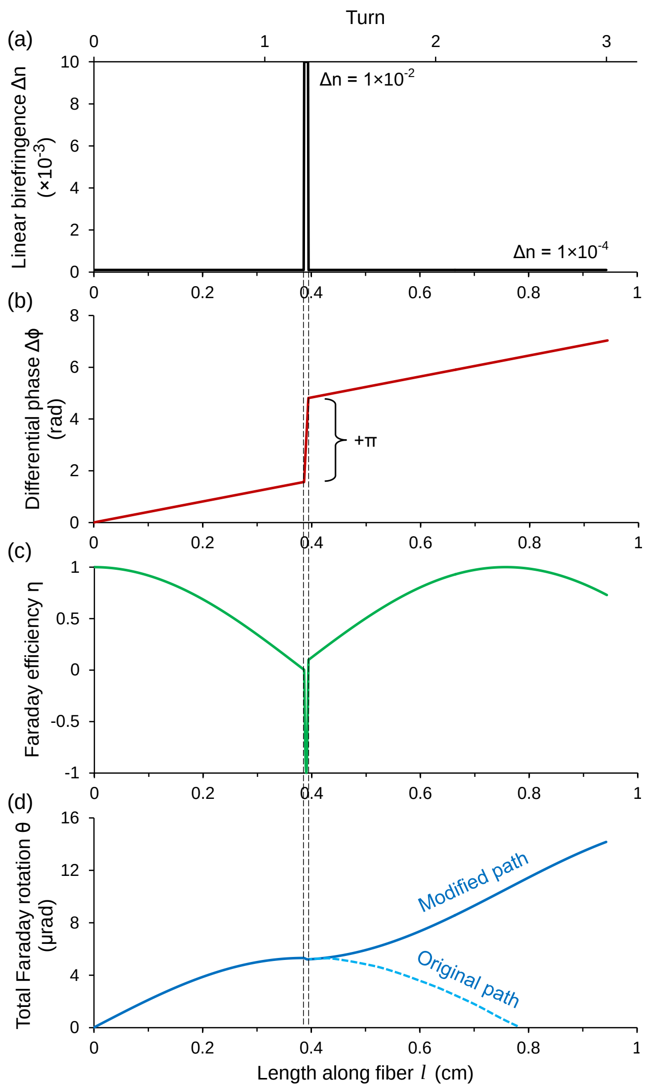

Fig. 2 *Simulations of birefringence modulation in a 3-turn MC (λ = 1550 nm, $\mu_0 = 4\pi\times10^{-7}$, $\mu_r = 1$, I = 10 A, V = 0.54 rad/T.m, r = 0.5 mm) to rectify the direction of Faraday rotation for an efficient build-up of current responsivity over fiber length.*
(a) Birefringence along the curvilinear axis of the OM
(b) Differential phase
(c) Faraday efficiency $\eta = \cos\left(\Delta\beta \cdot l\right)$
(d) Total Faraday rotation
The impact of changing the local birefringence in (a) is reflected in (b), (c), and (d).

This approach offers enormous flexibility and exceptional tolerance to fabrication imperfections and post-fabrication inaccuracies for improving the measurable Faraday rotation. Assuming that linear birefringence is uniform in coiled OM, the procedure involves measuring the beat length of a fabricated MC sample, before altering the local birefringence at initially a quarter of the beat length, and subsequently every half beat length interval. The modification of birefringence can be performed by femtosecond laser irradiation [8], or by any other means that has control over the magnitude and spatial length of modulation. The preciseness of the localized modification in terms of the position and width is not critical, as long as the change in differential phase can result in a rising Faraday efficiency to prolong the positive trend of the total Faraday rotation.

Conclusion: Non-ideal MC sensor heads can be revived for high-performance current sensing via the proposed birefringence modulation technique. The birefringence at selective regions along the OM is modified to manipulate the evolution of differential phase that results in continuous Faraday rotation. This post-fabrication technique is highly flexible and exhibits great tolerance to both fabrication imperfections and post-fabrication treatment inaccuracies. Furthermore, it can minimize resource- and time-consumption that will be beneficial for large-scale productions.

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