Spun optical microfiber

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Abstract—The first report of spun optical microfiber is presented, with details of the fabrication method and a demonstration of its important role in making practical Faraday-based microcoil current sensors. The recent emergence of such sensors has shown their potential for significantly higher bandwidth and compactness compared to conventional fiber-optic current sensors. We demonstrate that spun optical microfiber exhibits superior resistance to bend- and packaging-induced linear birefringence, which can improve the responsivity and reproducibility of the sensor head.

Index Terms—Spun optical microfiber, current sensing, birefringence.

I. INTRODUCTION

Current sensors that exploit the Faraday Effect [1-8] usually consist of an optical fiber coil wound 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 state is translated into an intensity modulation that provides a measure of current. However, the linear birefringence of the fiber can considerably influence the measured Faraday rotation. Recently, new approaches to current sensing using optical microfiber (OM) in the configurations of a microcoil (MC) and microcoil resonator (MCR) have been proposed and demonstrated [1,2]. They featured higher compactness and higher bandwidth. Although the minimum permissible bend radius of OMs is significantly smaller than those based on conventional fibers, the same problem of linear birefringence arises after packaging the compact device in ultraviolet-curable polymer for geometric and optical stability. In the presence of birefringence, the net power transfer between the fast and slow axes due to Faraday rotation is maximum after a quarter of a beat length, and reduces to zero over half a beat length.

Several solutions have been reported over the years. One technique uses a 45° Faraday rotator and a mirror to undo reciprocal linear and circular birefringence in the fiber. At the same time, the non-reciprocal Faraday rotation is doubled [3]. However, a complete cancellation of perturbation-induced effects is only possible for small rotation angles.

Another technique is to utilize highly birefringent (hi-bi) fiber with periodically spaced regions of current-induced circular birefringence to the fiber, which is effective for relatively large coils with few turns. For the MC/MCR, the amount of twist required to achieve a noticeable effect is likely to exceed the breaking strength of the OM. Additionally, the twists are temperature-dependent, incurring a stability issue.

The use of spun fibers is another solution to overcome the birefringence problem. This involves producing a low-birefringence fiber [8] by spinning the preform during fiber drawing to average the fast and slow birefringence axes. Again, when packaged in a coil the fiber suffers from bend-induced birefringence. As a result, spun hi-bi optical fibers [3] were introduced, which featured better resistance to external perturbations. Spun hi-bi optical fibers have sufficient circular birefringence to overcome the bend- and packaging-induced linear birefringence. Due to the effectiveness of the spun fiber technique and the feasibility for the OM to be spun in a similar fashion, it is of interest to study the spun optical microfiber (SOM) and its application for current sensing.

In this paper, we report the fabrication of SOM and demonstrate its important role in making practical MC/MCR-based current sensors. Additional applications include micro-resonator-based refractive index and temperature sensors that can benefit from sharper resonances. The minimization of linear birefringence can reduce the spectral shift of polarization-dependent resonant wavelengths that result in spectral dips of diminished Q-factor.

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II. SOM FABRICATION

The starting fiber of the SOM is a single-mode telecom fiber (SMF-28). The middle section of the fiber was processed while the two ends were kept as pigtails for easy integration with other fiberized components. To begin with, the acryllic coating of the fiber section of interest was removed with a fiber stripper. The fiber was then placed in the groove of a fiber holder and the folded edge of a fine-grade sand paper was used to carefully side-polish the fiber to produce a D-shaped section, as shown in Fig. 1. The polishing depth determines the linear birefringence of the tapered fiber. The required polishing length \( L_{SMF} \) on a section of SMF-28 with radius \( r_{SMF} \) for a given polishing depth \( d \), OM average radius \( (r_{OM}) \) and OM length \( (L_{OM}) \) can be approximated by calculating the cross-sectional area \( (A_{P-SMF}) \) of the polished fiber:

\[
L_{SMF} = \frac{\pi r_{OM}^2}{A_{P-SMF}} L_{OM} \quad (1)
\]

\[
A_{P-SMF} = \frac{2}{r_{SMF}} \left[ \pi - \cos^{-1} \left( 1 - \frac{d}{r_{SMF}} \right) - \frac{d}{r_{SMF}} + 1 \right] \quad (2)
\]

The range of polishing lengths is typically on the order of microns for OM lengths below 10 cm. The fine-grade sand paper has particles smaller than 3 \( \mu m \) and has been used to remove a few microns from the fiber surface in order to eliminate the circular symmetry typical of optical fibers. It is not essential to ensure that all linear birefringence is created precisely within the region to be tapered and spun. The tolerance to over-polishing can be drastically improved by tapering and spinning simultaneously. This minimizes linear birefringence outside the target region, where fiber polishing is already becoming increasingly less important as the mode is confined more and more into the core.

After polishing, the D-fiber section was rinsed with isopropanol to wash away any leftover debris. One end was securely clamped and the other end was fixed to the rotator module (Thorlabs Z-6 motorized rotator). The fiber clamp and holder plus rotator module were mounted on two individually controlled translation platforms. The microheater remained stationary. Tapers with a uniform waist diameter and taper transitions of configurable length and shape were produced by sweeping the two translation platforms back and forth along the D-fiber section while it is being heated. By carefully varying the differential motor velocities, the fiber can be stretched with sub-micron precision. This setup shown in Fig. 2 was used to produce both spun and unspun OMs.

To fabricate hi-bi OM, the D-fiber was initially softened by the ceramic microheater to reduce the surface roughness caused by mechanical polishing. This helped to prevent the formation of cracks that could break the fiber when subject to axial tension. After 1 minute of annealing, the D-fiber was tapered to the desired diameter and length without spinning. The final diameter was 2 \( \mu m \) to enable single-mode operation at a wavelength of \( \lambda = 1550 \) nm when embedded in polymer (EFIRON PC-373, \( n = 1.376 \)). The differential velocity of the translation platforms was varied to achieve a transition taper profile of \( \alpha = 0.3 \) [9]. The initial and final positions of the translation platforms were chosen to produce a uniform waist length of 1 cm. The resulting fiber shape was elliptical due to the surface tension of the partially melted silica. The current applied to the microheater was 3.2 A, corresponding to a temperature of \( \approx 1400 \) °C in the hot-zone.

The spin process of the SOM occurs in the microheater hot-zone, where the glass viscosity is sufficiently low to ensure a fully plastic deformation. The resulting fiber shape is circular due to the averaging effect of the spin process, as shown in Fig. 3. The spin rate \( (\tau \text{ rad/cm}) \) is ideally small and comparable with the linear birefringence \( (\Delta \beta = 2\pi n\alpha/\lambda) \), so that the linear birefringence is only partially cancelled by the spin process. A SOM with a high spin ratio \( (\tau/\Delta \beta) \) is sensitive to bending and applied stress, since high spin rates induce low linear birefringence [10]. For this reason, a high spin ratio was avoided to ensure isolation from external effects.

All samples were finally embedded in low refractive index polymer on a glass slide and ultraviolet-cured for geometric stability and protection against environmental effects.

![Fig. 2. Schematic diagram of the fabrication setup. A computer controls the movement of the two translation platforms and the rotator module.](image2)

![Fig. 3. Schematic diagram of spin optical microfiber with a constant spin rate \( \tau \text{ (rad/cm)} \) along fiber direction \( z \).](image3)

![Fig. 1. Cross-sectional view of (a) side-polished fiber, and (b) waist of tapered fiber. For the purpose of illustration, this diagram was not drawn to scale.](image1)
III. SOM Characterization

To determine the effect of spinning the OM, the linear birefringence of the hi-bi OM was compared with the linear birefringence of the corresponding SOM. The linear birefringence of an optical fiber is defined by its polarization beat length \( B_L \):

\[
B_L = \frac{2\pi}{\Delta \beta} = \frac{\lambda}{\Delta n}
\]  

(3)

To measure the \( B_L \), light from a tunable laser source (TLS) with a polarization-maintaining (PM) pigtail propagated through an in-line polarizer aligned at 45° to the axis of the fiber under test (FUT) of length \( L \), so that equal powers of light was transmitted along the fast and slow axes. The light from the two axes beat together at an analyzer set at 45° to the axis of the FUT. The transmission spectrum was captured by a photodetector connected to a digital oscilloscope. The linear birefringence is revealed as oscillations in the spectrum with a period of \( \Delta \lambda \). \( B_L \) can be calculated as follows:

\[
B_L = \left( \frac{\Delta \lambda}{\lambda} \right) L
\]  

(4)

The insertion loss of the samples is typically 0.5-1 dB after packaging. It can be seen from Fig. 4 that a spin rate of 8π/cm has increased the beat length of the hi-bi OM by a factor of 3. By doubling the spin rate to 16π/cm, \( B_L \) is increased by factor of 6. The varying extinction ratio is attributed to the output light of the TLS not being completely confined to one axis of the PM pigtail. Consequently, the degree of polarization of the light prior to the polarizer becomes wavelength-dependent and this affects the ratio of light in the two axes that beat at the analyzer. Nonetheless, it is evident that the beat length ratio between the spun and unspun OM can be changed by varying the spin rate.

Fig. 4. Transmission spectra of a 2 μm diameter hi-bi optical microfiber with \( L = 1 \) cm, \( \Delta \alpha = 3.23 \times 10^3 \) and the corresponding span microfibers with (a) \( \tau = 0 \) rad/cm, (b) \( \tau = 8\pi \) cm, and (c) \( \tau = 16\pi \) cm.

This allows SOMs to be made with high local birefringence to resist external perturbations, and spin-induced low effective linear birefringence to permit the full Faraday rotation to be measured.

It must be stressed that for SOMs with a diameter smaller than 10 μm, a significant portion of the guided mode(s) propagates in the polymer cladding outside the silica OM. Therefore, the averaging effect of spinning the fiber will be less than that of conventional spun fiber with the same spin rate. Fig. 5 shows the simulated relationship between effective linear birefringence (from spinning) and the final linear birefringence (after packaging). The effective indices were obtained by solving the eigenvalue equation of a circular cross-section waveguide [11]. It is clear that the effect of polymer packaging on SOM becomes negligible when the OM diameter is larger than 10 μm. Although the polymer packaging can reduce the linear birefringence to some extent, the material itself also contributes linear birefringence when cured and it tends to increase with time. Hence, by spinning the OM we not only reduce the bend-induced linear birefringence but also increase the tolerance to packaging-induced linear birefringence.

IV. Current Sensing

To demonstrate that MC current sensors based on SOM are more resilient to bend- and packaging-induced linear birefringence than those made using unspun OM, three MC samples were fabricated for each type of OM. All six samples were of 2 μm diameter and 30 mm length with \( \alpha = 0.3 \). A spin rate of \( \tau = 24\pi \) cm was chosen for the SOM samples. A thin layer of low refractive index polymer was deposited on a 1 mm diameter copper wire before and after coiling the fiber to ensure good confinement of light. Each MC had 7.5 turns with a large winding pitch (>0.5 mm) to prevent coupling between adjacent turns. Ultraviolet-curing of the polymer provided robustness. A photograph of the packaged sample can be seen in Fig. 6.

As shown in Fig. 7, a TLS feeds linearly polarized light into PM fiber that produces x and y-polarized light of equal power from a 45° splice angle. The polarization-maintaining coupler (PMC) allows the light to propagate through the sensing arm and back before separating the fast and slow components using a polarization beam-splitter (PBS) prior to signal analysis via a balanced detector (PD1+PD2) [2]. In the sensing arm, the
polarization state can be manipulated via a polarization controller (PC). A signal generator driving a transformer induces AC current along the copper wire that translates into a varying magnetic field. The Faraday-rotated light re-entering the PM fiber translates to an intensity modulation along the fast and slow axes. The Faraday rotator mirror (FRM) was used to double the rotation angle \( \theta \) of the light, expressed by:

\[
\theta = \mu_0 \mu VNI \mu \mu \theta 0 = VNI r \mu \mu \theta 0 \quad (5)
\]

where \( \mu_0 \) is the magnetic permeability of free-space, \( \mu \) is the relative permeability of silica, \( V \) is the Verdet constant of silica, \( N \) is the number of MC turns, and \( I \) is the magnitude of current.

The experimental results from Fig. 8 show that all SOM samples were able to achieve a responsivity of \( \approx 8.6 \, \mu \text{rad/A} \), approaching the theoretical value of \( 10.2 \, \mu \text{rad/A} \). In comparison, the three unspun samples showed less consistency with an average responsivity of \( \approx 5.7 \, \mu \text{rad/A} \). This indicates that spinning the OM before coiling offers better suppression of the linear birefringence in the packaged sensor head. Moreover, the performance of unspun OM is less predictable due to the build-up of linear birefringence during the coiling and packaging process.

V. CONCLUSION

In conclusion, we have proposed and demonstrated a simple yet cost-effective method to manufacture spun optical microfiber from SMF-28. Such fibers are very important for making practical microcoil-based current sensors that are more resilient to the effects of bend- and packaging-induced linear birefringence. The fiber polishing depth governs the linear birefringence of the hi-bi optical microfiber and thus the intrinsic linear birefringence of the spun optical microfiber. Circular birefringence was added by spinning the fiber during the tapering process to yield a lower effective linear birefringence that supports efficient Faraday rotation. Microcoil sensor heads made using spun microfiber exhibited higher responsivity and reproducibility than those made using regular unspun microfiber. This finding agrees with our expectations.

REFERENCES