Resonant Fiber Optic Gyroscope Using an Air-Core Fiber

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***Abstract*—Air-core photonic bandgap fibers (PBFs) have great potential for the resonant fiber-optic gyroscope (RFOG), because they reduce both the Kerr-induced drift and the thermal polarization instability. We experimentally studied an open-loop RFOG in which a 20-m resonant loop of 7-cell air-core fiber is closed by connecting the air-core fiber to a conventional single-mode fiber directional coupler. We measured a random walk of 0.055°/s$^{1/2}$ and a long-term drift with a standard deviation of 0.5°/s and a peak-to-peak variation of 2.5°/s over 1 hour. We discuss the sources of error in this RFOG and identify areas for future improvement. We project that with straightforward improvements, tactical-grade performance should be possible.**

***Index Terms*—Gyroscopes, photonic-bandgap fibers, resonant fiber-optic gyroscope, RFOG.**

I. INTRODUCTION

THE resonant fiber-optic gyroscope (RFOG) has the potential to offer high-performance rotation sensing in a package significantly smaller than conventional commercial fiber-optic gyroscopes (FOGs). This size advantage makes the RFOG very attractive for many applications where space is at a premium. While the RFOG has been studied extensively over the past three decades, two key problems, Kerr-induced drift and temperature-driven polarization instability, remain difficult to solve without greatly increasing complexity [1], and they have prevented the RFOG from becoming a commercial competitor to the FOG. Air-core photonic-bandgap fibers (PBF) have been shown to reduce the Kerr-induced drift in the FOG [2], and measurements indicate that they can also mitigate the thermal polarization instability [3]. Thus, air-core fibers offer a novel approach to overcome the main problems present in conventional solid-core RFOGs, which may allow for the RFOG to be commercialized. With these potential benefits in mind, we have undertaken an experimental study of an RFOG with a sensing coil made from an air-core PBF.

The introduction of an air-core fiber in an RFOG unfortunately also gives rise to a new set of problems. Foremost among these challenges is the fact that directional couplers for air-core PBF do not yet exist, so the resonant loop in the air-core RFOG must be closed in some other way. This coupling must exhibit low loss and exceedingly low back-reflection [4], as discussed further on, which means that reflections at air-silica interfaces must be handled carefully. Additionally, current commercial air-core fibers have a higher loss and backscattering than conventional fibers, both of which are generally undesirable in an RFOG.

In this paper, we first review the theoretical advantages of utilizing an air-core fiber in an RFOG. We then describe our experimental air-core RFOG and its measured performance characteristics. With our current design, we measured a random walk of 0.055°/s$^{1/2}$ and a long-term drift with a standard deviation of 0.5°/s and a peak-to-peak variation of 2.5°/s over 1 hour. These figures set the first quantitative landmarks in rotation sensing using an air-core fiber in an RFOG. While these figures are several orders of magnitude worse than the performance of a high-end commercial FOG (for example, a random walk of 0.0002°/h$^{1/2}$ and a bias stability over 1 h of 0.002°/h (3σ) is posted in [5]), we anticipate that they should be significantly improved by implementing a number of straightforward modifications, discussed at the end of this paper.

II. A REVIEW OF THE RELEVANT PHYSICAL PROPERTIES OF AIR-CORE PBF

Air-core photonic-bandgap fibers consist of a hollow central core surrounded by a photonic crystal made of air holes in a solid cladding. Most (typically 95% or more) of the energy in the guided modes is confined within the air core, and the rest in the membranes (made of silica in this application) between holes. Since light propagates mostly in air, the physical properties of an air-core PBF are quite different from those of conventional fibers, in which light travels entirely in a solid (typically silica).

One of the key benefits of air-core PBFs for optical gyroscope applications is a large reduction in the Kerr effect. The Kerr effect is a nonlinear, power-dependent process that induces a nonreciprocal phase shift in the sensing fiber of both FOGs and RFOGs. This phase shift results in a drift in the gyroscope output. The Kerr phase shift is given by $\phi_k = \Delta P \eta \gamma_k L$, where ΔP is the difference in powers between the clockwise and counterclockwise signals in the sensing coil and γ_k is the Kerr coefficient of the fiber. The factor η accounts for the effect of polarization. In an RFOG, the two counter-propagating signals are both launched along one of the fiber coil's polarization eigenstates and $\eta = 8/9$ [2]. The Kerr coefficient γ_k is inversely proportional to A_{eff}, the effective area of the fiber mode and n_2, the nonlinear index of refraction seen by the fiber mode. Both air-core and solid-core fibers have similar values of A_{eff}, but in an air-core fiber most of the power propagates in air, which has a much smaller n_2 than the doped silica of a solid-core fiber.

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Thus, the Kerr coefficient γ_k is much smaller in an air-core fiber. For a 7-cell fiber (HC-1550-02 from NKT Photonics), simulations and experiments indicate that γ_k is $\sim$250 times smaller than in a Corning SMF-28 fiber [2]. This figure depends on the fiber design. For example, 19-cell PBFs confine a larger fraction of the power to air and exhibit larger mode effective areas than 7-cell PBFs; both effects further reduce γ_k. To date, the lowest reported γ_k value in a 19-cell PBF is $\sim 2.5 \cdot 10^{-3}$ rad/W/km [5] (~ 415 times lower than in an SMF-28 fiber). This particular PBF was not designed for the purpose of minimizing the Kerr effect. We speculate that with an optimized design, a 19-cell PBF could have a γ_k smaller than 10^{-3} rad/W/km. Straightforward calculations indicate that current 7-cell PBFs can reduce the drift due to the Kerr effect in an RFOG to below the tactical-grade level. If 19-cell PBFs suitable for the RFOG (i.e., essentially single-moded and polarization-maintaining (PM)) are developed, the Kerr-induced drift could be reduced to inertial-grade levels.

The second main source of error in solid-core RFOGs is drift due to thermally driven polarization instabilities in the ring resonator. A thorough discussion of this subtle effect can be found in [7], [8]. Briefly, the fiber ring resonator of an RFOG has two polarization eigenstates. Due to birefringence, these two eigenstates have different effective indices, and hence different resonant frequencies. Most of the optical power is purposely launched into one eigenpolarization only. However, some power is always inadvertently coupled to the unwanted eigenpolarization. When the fiber temperature varies, the resonance frequencies of this unwanted eigenpolarization move with respect to the resonance frequency of the primary eigenpolarization that is interrogated, to a large extent because the fiber beat length L_b depends on temperature. This causes a small but measurable apparent change in the resonance frequency of the primary eigenpolarization. Since this change occurs on a long time scale, it manifests itself as a drift, also indistinguishable from a rotation-induced change in frequency. Other groups have reported qualitative [3] and quantitative [9] measurements demonstrating that dL_b/dT can be much smaller in air-core fibers than in conventional fibers, which suggests that these fibers should reduce errors due to thermal polarization instability.

Another advantage of PBFs in gyroscopes is a reduction in the impact of two deleterious thermal effects. The first one is the Shupe effect: time-varying temperature gradients present in the sensing coil induce a *nonreciprocal* phase shift between the counter-propagating signals, which is also indistinguishable from a rotation [10], [11]. The angular pointing error due to this effect is proportional to the coil length L and to the fiber's Shupe constant $S = \alpha + (1/n_{\text{eff}}) \cdot dn_{\text{eff}}/dT$, where α is the thermal expansion coefficient of the fiber and dn_{eff}/dT is the temperature dependence of the fiber mode's effective index. In an air-core fiber, dn_{eff}/dT is much smaller than in a solid-core fiber, and S is significantly reduced, for example by a factor of about 5 in a 7-cell fiber [11]. Since RFOG coils are typically much shorter than FOG coils, the Shupe effect is generally much smaller in RFOGs [10], [13], and it has not been reported as a major source of drift. However, it may not be negligible for all applications, and the use of an air-core fiber may have the additional benefit of further reducing it.

The second thermal effect is that a varying temperature also induces a much larger *reciprocal* phase shift (common to both counter-propagating signals). This effect is typically cancelled out by a feedback system. Using a PBF in an RFOG also reduces this effect, which reduces the dynamic range required of the feedback system. Just like the Shupe effect, this dynamic range was never reported to be an issue in solid-core RFOGs, so this attribute of PBFs may not be relevant, but it may be beneficial for high-accuracy systems.

The Faraday effect is a nonreciprocal polarization rotation induced by external magnetic fields (such as Earth's field) that leads to a drift in the output of a fiber-optic gyroscope. The strength of this effect in a given fiber is governed by the Verdet constant V. Measurements show that V is reduced by a factor of about 90 in HC-1550-02 air-core fiber compared to an SMF-28 fiber [14]. While the Faraday effect is not a main source of drift in experimental RFOGs, this reduction may be beneficial in some future high-sensitivity RFOG applications.

Commercial, nominally single-mode PBFs currently have significantly greater propagation loss and backscattering than a conventional fiber. Specifically, an SMF-28 fiber has a loss around 1550 nm of $\sim$0.3 dB/km, whereas the HC-1550-02 fiber has a loss of $\sim$20 dB/km, and the HC-1550-04 fiber a loss $\sim$12 dB/km. In an RFOG, increased propagation loss reduces the resonator finesse and hence the sensitivity. Backscattering is also a significant source of error [15], [16]. The total power backscattered by a fiber is proportional to $S\alpha_s$, where S is the recapture factor and α_s the backscattering coefficient. In current commercial PBFs, $S\alpha_s$ is at least one order of magnitude greater than in a low-loss single-mode fiber. For example, the HC-1550-02 fiber has been predicted to have an $S\alpha_s$ of $1.5 \cdot 10^{-6}$ m^{-1} [17], while in the SMF-28 fiber it is $\sim 6 \cdot 10^{-8}$ m^{-1}. A 19-cell air-core PBF has a much lower loss (1.2 dB/km was demonstrated in [18]), and consequently it likely also has a lower backscattering coefficient. However, these fibers are currently multimode and do not maintain polarization, which makes them poorly suited for the RFOG.

III. EXPERIMENTAL RFOG

To experimentally study the applicability of air-core PBF in an RFOG, we constructed the open-loop RFOG shown in Fig. 1. It operates similarly to other open-loop RFOGs reported in the literature. In particular, the modulation and locking schemes employed here were adapted from [15], which offers a good description of these techniques. The sensing coil consisted of 20 m of PM PBF (HC-1550-PM-01 from NKT Photonics) cylindrically wound around a mandrel with a 7.6-cm diameter. To form the ring resonator, the coil was closed using a conventional fiber directional coupler with a 10% power coupling ratio. The PBF coil was connected to the coupler pigtails using one of two methods discussed below. The ring was probed with a tunable 1550-nm laser with a 2.2-kHz full-width-at-half-maximum (FWHM) linewidth. The laser frequency was sinusoidally modulated at 20 kHz, and the output of one detector (the ccw detector in Fig. 1) was demodulated by a lock-in amplifier (LI_1 in Fig. 1)

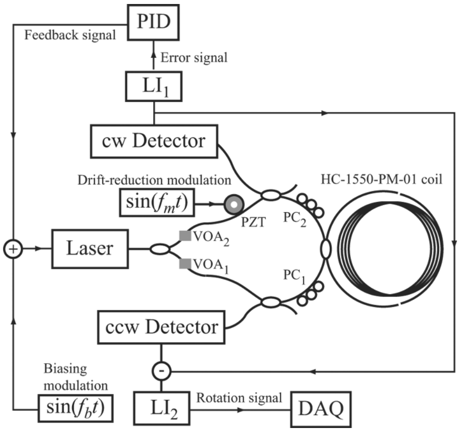

Fig. 1. Configuration of the experimental air-core resonant fiber-optic gyro.

to generate an error signal [15]. This signal was processed by a proportional-integral-derivative (PID) controller, which applied the appropriate feedback to the tunable laser frequency to keep the ccw mode locked on a resonance. A second lock-in amplifier (LI_2) was used to generate the rotation signal, which is the demodulated difference between the cw and ccw signals. Polarization controllers (PC_1 and PC_2) were used to ensure that the cw and ccw signals in the coil had the same polarization, and variable optical attenuators (VOA_1 and VOA_2) were used to ensure that they had the same power. The coil was placed in a thermally insulated container, and the optical portion of the gyroscope mounted on a motorized rotation stage located outside the container. The rotation signal was recorded by a digital data acquisition system. For calibration, the gyroscope was rotated at a known rate.

Both discrete reflections [4] and distributed (e.g., Rayleigh) backscattering [16] degrade the performance of an RFOG. The total electric field at the cw detector consists of two components: the primary field that circulated through the ring clockwise, and the reflected and backscattered portions of the counterclockwise signal. Similarly, the total field at the ccw detector consists of the ccw primary field and the cw reflected and backscattered fields. The relative phases of the primary and reflected fields at each detector vary randomly due to thermal variations in the lead fibers (i.e., the fibers between the laser and the resonator) and in the coil. The interference between these signals results in a drift in the output signal. To reduce this drift, we implemented a common drift-reduction modulation scheme [15]. One input to the resonator (ccw in Fig. 1) was sinusoidally modulated at a frequency f_m by a PZT placed on an input fiber leading to the ring, while the other input (cw) received no modulation. The total electric field at each detector then consisted of a modulated component (either primary or reflected) and an unmodulated component (either reflected or primary). The modulation amplitude was adjusted to suppress the optical carrier frequency as much as possible, which shifted most of the low-frequency drift (the interference between the primary and reflected signals) by multiples of f_m. Generally, f_m falls outside the detection bandwidth of the lock-in amplifier that generates the rotation signal (LI_2), so the lock-in amplifier filters out and greatly attenuates the signal components at multiples of f_m. We additionally applied narrow-band notch filters around these frequencies in our data analysis to remove the residual signal not filtered out by the lock-in amplifier. Experimentally, we adjusted both f_m and the modulation amplitude to minimize the observed drift.

As a baseline, we first evaluated the performance of this same RFOG when the PBF coil was replaced by a coil of conventional fiber. The resonator then consisted of 20 m of SMF-28 fiber wound in a 7.6-cm diameter coil and spliced to a 10% directional coupler. The measured finesse of this resonator was 25, and its measured resonance FWHM was about 420 kHz. The measured random walk of this RFOG was $0.004°/\mathrm{s}^{1/2}$, which corresponds to a minimum rotation-induced frequency shift of $\sim$2.5 Hz with a 1-Hz detection bandwidth. This random walk lies within our experimental error of a previously reported value for an open-loop RFOG [15], once differences in scale factor and finesse are accounted for. The measured peak-to-peak drift over a 2-minute interval was $0.027°/\mathrm{s}$, which again is close to the value published in [15] after correcting for differences in scale factor and finesse. This study confirmed that our RFOG performed as expected when its resonator was made of solid-core fiber.

While air-core PBF ring resonators made using free-space coupling with bulk optics have been demonstrated [3] and shown to have very low loss ($< 7\%$), this method is not straightforward, and we opted to close the PBF coil using a simpler all-fiber approach instead. The loop was closed using a conventional single-mode fiber (SMF) directional coupler with short leads connected to the air-core fiber coil (see Fig. 1). For convenience, the leads were kept somewhat long ($\sim$1 m each), but in future designs they could be much shorter (< 2 cm). Our measurements indicate that Kerr-induced errors introduced by these solid-core fiber leads are small compared to other sources of drift.

Within the ring there are two junctions between the fiber-coupler fiber leads and the PBF. At each junction, light must be coupled between dissimilar fibers, ideally with very little loss and back-reflection. Although splices between a conventional SMF and a PBF with relatively low loss have been demonstrated [19]–[21], such splices are unacceptable for an RFOG because of the large ($> 3.5\%$) Fresnel reflection between the air-core and solid-core fiber. By angling the two fiber ends before splicing, this reflection has been reduced to -60 dB [22], but the loss remains high ($\sim$3 dB) because of refraction between the two fibers. To reduce this reflection while keeping the loss below this value, we experimentally studied two different ways to couple the SMF and PBF.

The first method consisted in applying an anti-reflection (AR) coating to the ends of the SMFs. The reflectivity of the PBF/SMF interface was then reduced from -14 dB to about -35 dB. Since splicing an AR-coated SMF to the PBF expectedly destroyed the coating, the two fibers were butt-coupled using mechanical stages. The AR-coated SMF and PBF tips were in physical contact to improve the mechanical stability. This method produced a coupling loss of $\sim$2.1 dB per junction, primarily due to mode size and shape mismatch between the fibers. Combined with the propagation loss ($\sim$0.1 dB) of the

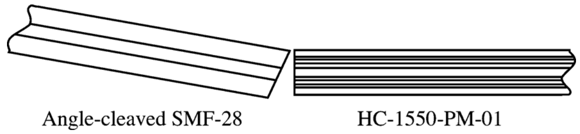

Fig. 2. Air-core PBF coupled to angle-cleaved SMF-28.

20-m coil, this resulted in a round-trip loss of $\sim$4.3 dB, and a finesse of $\sim$5.8, confirmed by measurements.

The second method was to cleave the SMF at an angle (see Fig. 2) so that power reflected at the SMF/air interface was not captured by the SMF mode. This lowered the reflectivity of the SMF/air interface to around -60 dB. The reflectivity at the end of the other fiber (PBF/air interface), which was not angle-cleaved, produced the usual very weak reflection that occurs at the cleaved end of an air-core fiber placed in air. While there are no published values for the reflectivity of this particular PBF, a reflectivity of -57 dB was predicted for a similar PBF in [23], and we expect a comparable value for this fiber. Again the two fiber tips were aligned using mechanical stages. The fiber tips were not in physical contact. To minimize the coupling loss, the SMF and PBF must be angled with respect to each other (see Fig. 2), since the signal refracts at the SMF/air interface. Using this method, we were able to achieve a coupling loss of $\sim$2.7 dB per junction, for a round-trip loss of $\sim$5.5 dB and a finesse of $\sim$4.2. This second method has somewhat greater loss but significantly lower reflection.

IV. MEASURED PERFORMANCE OF THE AIR-CORE RFOG

The performance of our air-core RFOG was quantified experimentally in terms of its random walk (or noise) and drift. To measure the noise, we recorded the rotation signal output from our gyroscope while it was stationary, varying the time constant τ of lock-in amplifier LI_2 from 100 ms to 3 ms. For the fourth-order low-pass filter used in the lock-in amplifier, the noise equivalent bandwidth was $BW_e = 5/(64\tau)$. For each value of τ, three measurements of the RFOG output trace over time were performed, each for a two-minute duration. To obtain the noise, this data was digitally processed with a notch filter to remove all frequency components with a frequency under 0.2 Hz, as these slow variations are characteristic of drift, not noise. Additional narrow (2-Hz width) notch filters were used at f_m and its harmonics as a part of our drift-reduction scheme. The noise was calculated by taking the standard deviation σ of the filtered data. The random walk was calculated by computing numerically the average value of $\sigma/BW_e^{1/2}$. We measured a random walk of 0.13°/s$^{1/2}$ in the air-core RFOG with the AR-coated connections, and 0.055°/s$^{1/2}$ with the angle-cleaved connections. These two values are more than two orders of magnitude greater than the shot-noise limit.

To obtain the drift, we calculated the variation in the output signal for longer time durations, without filtering out the low-frequency components of the output signal. For all drift measurements, a 100-ms time constant ($BW_e = 0.78$ Hz) was used. The maximum observed peak-to-peak drift over a 2-minute measurement was $\sim$ 2°/s with AR-coated connections, and $\sim$ 1°/s with angle-cleaved connections. Turning off the drift-reduction modulation increased the drift measured over a 2-minute interval by $\sim$18 dB. We also measured the long-term drift with angle-cleaved connections. The peak-to-peak drift over 1 h was 2.5°/s, and the standard deviation σ was 0.5°/s. The RFOG output trace of this measurement is shown in Fig. 3. Table I summarizes the measured random walk and short-term drift.

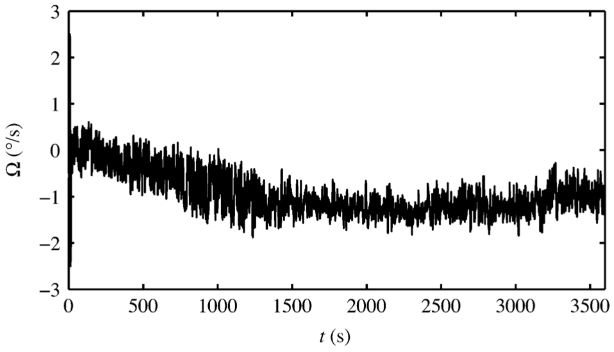

Fig. 3. Long-term drift measurement data. The spike near $t = 0$ is a $\pm 2.5°$/s calibration rotation.

TABLE I
MEASURED FINESSE, RANDOM WALK AND DRIFT FOR THE TWO AIR-CORE RFOGS

SMF-PBF connection	Finesse	Random walk	Drift (p-p over 2 min)	Drift (p-p over 1 h)
AR-coated	~5.8	0.13 °/s$^{1/2}$	~2 °/s	—
Angled	~4.2	0.055 °/s$^{1/2}$	~1 °/s	2.5 °/s

V. DISCUSSION OF DRIFT AND NOISE

These experimental results indicate that the air-core RFOG using angle-cleaved junctions has lower random walk and lower drift than the RFOG with AR-coated junctions, in spite of the lower finesse of the former. Since the two RFOGs were otherwise identical, it suggests that the discrete reflections at the SMF/PBF interfaces are significant sources of both drift and noise in the RFOG with AR-coated fibers. We modeled the effect of these reflections on the drift and noise in our air-core RFOG to see if they could explain the observed errors.

A. Drift Analysis

Using a method similar to that described in [4], we numerically modeled the drift due to discrete reflections at the SMF/PBF interfaces. Simulation results confirmed that when AR-coated fiber tips were used, these reflections were likely the dominant source of drift. On the other hand, in the RFOG with angle-cleaved fiber tips, they predicted that the residual reflections from the interfaces ($\sim$ -60 dB) were much too small to explain the observed drift. The drift in the RFOG with angle-cleaved fiber tips is therefore due to some other effect. Thus, either the discrete reflections at the junctions were much larger than expected, or the drift in the RFOG with angle-cleaved SMF tips is due to some other effect.

One probable cause of this observed drift is backscattering from the fiber coil. We estimated that the total fraction of input power backscattered by the coil (given by $S\alpha_s L$) is around

$2 \cdot 10^{-5}$, which is significantly larger than the fraction of power reflected at the SMF/PBF interfaces. We thus intuitively expect that the drift due to backscattering is greater than the drift due to discrete reflections. While other groups have studied distributed backscattering in an RFOG [16], there is unfortunately no published model for estimating this backscattering-induced drift. Fig. 3 shows that the drift in this RFOG exhibits strong variations over 10-s to 20-s time intervals. The presence of drift on this time scale suggests that a spurious interferometer may be present in the RFOG, with the path lengths of its arms randomly fluctuating due to temperature variations, as would be expected if the drift originated from backscattering. This interferometer is likely formed from the interference of the backscattered and primary signals, whose relative phases vary randomly due to thermal variations in the lead fibers and the fiber coil.

While our experimental observations are consistent with the hypothesis that the observed drift is due to backscattering, additional experiments and analysis are required to conclusively identify the dominant drift mechanism. Besides backscattering, other possible sources of drift include mechanical instability of the SMF/PBF junctions, interference between PBF modes, and interference-type thermal polarization errors.

B. Noise Analysis

While the finesse of our air-core RFOG with angle-cleaved connections was approximately one sixth of that in our solid-core RFOG, the random walk in our air-core RFOG was about 14 times greater than in the solid-core RFOG. All else being equal (i.e., for the same signal-to-noise ratio), the random walk of an RFOG is expected to scale inversely with finesse [10]. Therefore this reduction in finesse alone cannot explain the reduction in performance; we suspect that the air-core RFOG exhibits greater noise (and hence a lower *SNR*) than the solid-core RFOG. We surmise that this additional noise is likely caused by either the physical properties of the PBF, or the method used to close the loop. We constructed a model for the random walk due to the discrete reflections at the SMF/PBF interfaces via the phase noise in the laser source, following the method outlined in [24]. The interference between the primary and reflected fields at the detector contains intensity noise, because the source has phase noise and the two signals emerged from the source at different times. We estimated the total noise by calculating the noise due to the interference of the largest components of the primary and reflected fields. For both air-core RFOGs (AR-coated and angled connections), the random walk predicted by this model is much smaller than the observed noise, because the linewidth of our source (and hence its phase noise) was so small. Further investigations are necessary to determine the noise sources limiting the random walk in both cases.

VI. FUTURE IMPROVEMENTS TO THE AIR-CORE RFOG

Currently, the random walk and drift in our experimental air-core RFOG are about 6 and 180 times greater than tactical-grade values [25]. We have identified two key areas where straightforward modifications of our current prototype could yield significant performance improvements.

A. Improving the Finesse

To increase the finesse of our current resonator (4.2), the dominant source of loss, which is coupling at the two connections, must be reduced. This can be accomplished in one of four ways. The first one is to close the loop using bulk mirrors and lenses instead of a fiber coupler. This solution has led to an air-core fiber resonator with a finesse of 42 [3]. The second approach, more speculative, would be to use a PBF with a mode that is better matched to that of the SMF from the coupler. Even optimized connections between an SMF and currently available PBFs have appreciable loss due to mode-shape mismatch (0.79 dB was reported in [21] using an HC-1550-02 PBF and a single-mode fiber with optimized mode-field diameter and V number), so a new PBF needs to be developed to significantly increase the finesse. The third approach is to close the loop using micro-bulk-optic couplers, such as those detailed in [26]. At best, we expect a micro-bulk-optic coupler to perform comparably to conventional bulk-optic coupling, so a ~10-fold enhancement in finesse may eventually be possible with this method. The fourth method is to use a directional coupler made from air-core PBF, if such a device is developed. This would be an ideal solution, since such a coupler would be expected to exhibit much lower loss and backscattering than other methods.

Absent a clear theoretical understanding of the dominant noise sources in our air-core RFOG, it is difficult to estimate the performance impact that an improvement in finesse would yield. As mentioned above, for a given signal-to-noise ratio *SNR*, the random walk in an RFOG is inversely proportional to F. But the relationship between the *SNR* and the finesse depends on the physical origin of the noise. Similarly, the amount of drift reduction expected for a given finesse improvement depends on the source of the drift. At best (i.e., if the *SNR* due to the dominant source of error is independent of F), the noise and drift in our RFOG could scale like $1/F$. At worst (i.e., if increasing F decreases the *SNR*), the random walk could decrease much more slowly (or perhaps not at all) with F. Further analysis and modeling are necessary to quantify the exact performance improvement that an enhancement in the finesse would yield.

B. Reducing Errors Due to Backscattering

Our observations and analysis suggest that backscattering may be a significant source of error in our current RFOG. If so, the backscattering-induced noise and drift can be reduced using one of several methods. The first one is to utilize a fiber with less backscattering. For the sake of argument, let's assume that the 7-cell PM PBF used in our air-core RFOG had an $S\alpha_s$ of 10^{-6} m^{-1} (i.e., a little lower than for the HC-1550-02 fiber, which has a slightly higher loss but may not scatter as much because it does not have added beads to maintain polarization). In the future, it may be possible to make an air-core RFOG from a PBF with a much lower value of $S\alpha_s$. The ultimate limits to backscattering in air-core PBF [27] have been predicted to be as low as $S\alpha_s \approx 7 \cdot 10^{-10}$ m^{-1} for 7-cell fiber and $S\alpha_s \approx 7 \cdot 10^{-11}$ m^{-1} for 19-cell fiber. Errors due to backscattering are expected to scale like $(S\alpha_s)^{1/2}$, since they result from the interference of the primary signal field with the backscattered signal field.

Then these predicted ultimate backscattering limits would reduce the errors due to backscattering by factors of ~ 40 for the 7-cell fiber, and ~ 120 for the 19-cell fiber. These predictions have not yet been independently verified or experimentally realized, however. While lowering the backscattering to the levels predicted in [27] may prove difficult, it is reasonable to speculate that that future 19-cell PBFs may reduce $S\alpha_s$ (and thus the backscattering-induced errors) to levels comparable to conventional single-mode fibers, if not lower.

The second method is to improve the drift-reduction modulation scheme. In our current RFOG, as mentioned earlier we observed about 18 dB of reduction in the drift with the drift-reduction modulation scheme. More effective modulation schemes have been demonstrated in solid-core RFOGs, and it would be straightforward to apply these techniques in a future air-core RFOG. For example, Hotate *et al.* showed in [28] that with appropriate square-wave modulation, the drift due to backscattering in a solid-core RFOG could be reduced by more than 40 dB. Triangle-wave modulation [29] has also been proposed as an improvement over sinusoidal modulation. Both of these modulation schemes serve the same purpose (optical carrier suppression) as the sinusoidal modulation scheme that we employed, but they also benefit from more lenient tuning requirements: the modulation index does not need to be controlled as precisely in order to achieve a given reduction in the drift. By adopting one of these schemes it should be possible to reduce the backscattering-induced drift by as much as 22 dB. The modulation schemes discussed above would also reduce the drift due to discrete reflections (e.g., reflections from fiber endfaces), for the same physical reasons.

Finally, it may be possible to reduce the performance degradation due to backscattering by adopting some of the techniques reported in conventional RFOGs, including digital serrodyne modulation [30] and bipolar digital serrodyne modulation [31].

VII. PROJECTED FUTURE PERFORMANCE

With the same HC-1550-PM-01 fiber as in our current prototype, a 10-fold increase in F (possible with bulk-optic or micro-bulk optic coupling) could, at best, reduce the random walk to $0.0055°/\mathrm{s}^{1/2}$, below the tactical-grade limit of $0.0083°/\mathrm{s}^{1/2}$. Other straightforward improvements (e.g., lower mechanical noise) could further reduce the random walk without changing the type of fiber. If the random walk is due to backscattering, significant additional reductions in the random walk could be possible with future fibers, as mentioned above.

If backscattering is the dominant source of drift in our current gyroscope, as discussed above, a better modulation scheme should reduce the backscattering-induced drift by up to 22 dB. This improvement alone would be sufficient to reduce the drift to $\sim 0.003°/\mathrm{s}$, comparable to the tactical-grade limit of 0.0028°/s. Additionally, future PBF designs could reduce the backscattering-induced drift by as much as another factor of ~ 120 (for the 19-cell PBF mentioned above), putting the backscattering-induced drift comfortably below tactical-grade levels, though still larger than the inertial-grade limit by approximately one order of magnitude.

Conservative estimates of the Kerr-induced drift in an air-core RFOG show that it should be on the order of 10^{-5}°/s with current 7-cell air-core fibers. This is well below both the tactical-grade limit and the observed drift level in solid-core RFOGs. With existing 19-cell fibers, the Kerr-induced drift is further reduced by about one order of magnitude, which would bring this source of drift below the inertial-grade level ($\sim 3 \cdot 10^{-6}$°/s). Therefore if a PM 19-cell fiber that is essentially single-mode is developed, such a fiber will be able to reduce the Kerr drift sufficient for an inertial grade RFOG.

We are currently investigating the reduction in drift caused by thermal polarization errors in an air-core RFOG. This drift limits the range over which the temperature of the fiber coil can be allowed to vary. For intensity-type errors, the relevant fiber parameter that governs this temperature range is $J = 1/L_b^2 \cdot dL_b/dT$, where L_b is the fiber's birefringence beat length [32]. A model utilizing the measured value of J for the HC-1550-PM-01 fiber predicts a 3-fold improvement in temperature range over a conventional elliptical-core polarization-maintaining fiber, and about a 10-fold improvement over a PANDA fiber [32]. The parameter J depends on the fiber design, and it is possible that future PBFs will offer an even broader temperature range. Further research is needed to assess the quantitative reduction of the overall drift due to thermal polarization instabilities (including drift due to interference-type errors) possible with a PM PBF. Other groups have successfully eliminated much of this drift in solid-core RFOGs by using rotated splices within the sensing coil [3], [33]. These techniques require extremely precise and difficult splices, and splices add undesirable loss and reflection to the ring. It is therefore preferable to solve this problem entirely by using an air-core fiber. This splicing technique can nevertheless be implemented in an air-core RFOG if additional drift reduction is necessary. As mentioned earlier, other sources of error due to the modal and polarization properties of the PBF may also be present. Additional work is necessary to quantify these errors and identify potential countermeasures.

The bottom line is that it is reasonable to expect tactical-grade performance from a next-generation air-core RFOG with a few straightforward improvements (higher finesse and improved drift-reduction modulation), without requiring the development of any new air-core fibers. Much better performance may eventually be possible with improved fibers and a better understanding of the error mechanisms in the air-core RFOG.

VIII. CONCLUSION

In conclusion, this is the first public report of an experimental RFOG using an air-core PBF as the sensing coil. The use of an air-core PBF in this application is very promising because it significantly reduces the drift due to the Kerr effect and thermal polarization instabilities. In this first-generation air-core RFOG, we measured a random walk of $0.055°/\mathrm{s}^{1/2}$ and a long-term peak-to-peak drift of 2.5°/s with a standard deviation of 0.5°/s over 1 h. These two parameters can be improved by increasing the finesse of our current RFOG, implementing a more advanced modulation scheme, and/or using an air-core fiber with a lower backscattering, such as a 19-cell fiber. With these improvements, we project that a second-generation air-core RFOG can reach tactical-grade performance.

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