1. Introduction

The Resonator Fiber Optic Gyroscope (RFOG) has great potential as a next-generation guidance and navigation technology. This is because it combines the sensitivity advantages of multi-turn coils used in interferometric fiber optic gyros with the enhancements afforded by the recirculation of light in a resonant cavity. Over a decade ago, the use of hollow-core fiber (HCF) in the resonator sensing path was proposed to overcome many of the historical drift mechanisms and barriers attributed to the employment of monochromatic light in conventional glass-core fibers [1]. Despite the appeal of this concept, practical problems—mostly linked to insufficient modal purity in the fiber—have until recently prevented demonstrations of an HCF-based RFOG with good performance. In this paper, we present, for the first time, the use of single-mode, anti-resonant nodeless HCF in an RFOG and show that the excellent properties of the fiber enable us to measure long-term bias stability down to 0.05 deg/hr over 1-10 hours. This represents a 3X improvement over the best previously reported result [2], and is achieved over the multi-hour integration times required for inertial navigation. For integration times longer than 1 hour, this represents an improvement of more than 500X. This stability highlights the attractive properties of nodeless antiresonant fibers in resonator applications and brings the performance of HCF-based RFOGs to within an order of magnitude of that required for civil aircraft navigation.

In the RFOG, rotation rate is measured by determining resonant frequency shifts between the clockwise (CW) and counterclockwise (CCW) light propagation in a multi-turn passive fiber ring resonator [3,4], as shown in Fig. 1. In this arrangement, CCW and CW laser waves at $f_0$ and $f_0 + \Delta f$ are precisely tuned to the centers of CCW and CW resonances of a fiber ring resonator to determine their resonance frequencies. In the presence of rotation, the resonances are shifted, and the laser input frequency difference, $\Delta f$ is proportional to rotation rate $\Omega$, via $\Delta f = (D/n\lambda)*\Omega$, where $D$ is the coil diameter, $\lambda$ the wavelength, and $n$ is the refractive index of the fiber core.

The use of a high power, narrow linewidth laser to interrogate the high-finesse resonator can present significant challenges for conventional solid-core fibers, as both linear and non-linear interactions between the optical field and the glass produce a multitude of spurious...
signals, such as stimulated Brillouin scattering, Kerr nonlinearity [5], coherent backscatter [6], and polarization effects [78]. These give rise to an erroneous indication of rotation rate, or bias instability. The nonlinear effects impose optical power limits (lowering SNR), and tight power control requirements, while in the latter two cases, use of a narrow linewidth laser allows light in potentially a multitude of spurious paths to be fully coherent with signal light traversing the resonator. Thus, polarization effects and backscatter impose tight constraints on the resonator fiber, since distributed backscattering or modal couplings at disparate and distant sites along the fiber can interfere coherently. Because these spurious signals are dependent on minute environmental perturbations, they can severely compromise RFOG bias stability.

The ideal waveguide for an RFOG is thus one in which the optical field is confined in a low nonlinearity material such as air or vacuum (i.e. an HC), in which only a single spatial mode is guided with low loss, low polarization crosstalk, and low backscatter [1]. Th e first demonstration of HC in a resonator for rotation sensing used a Hollow-Core Photonic Bandgap Fiber (HC-PBGF) with free-space beamsplitters for the input/output optics and achieved a finesse of 42 [1]. Dignam and colleagues demonstrated that HC-PBGFs could be used to reduce nonlinearity and environmental sensitivity in an interferometric fiber gyro (IFOG) [9], and reported the first measured performance of an RFOG based on HC-PBGF, with a long-term stability of 1800 deg/hr at an integration time, $\tau$, of 1 hour [10]. By using a polarization maintaining HC-PBGF and a hybrid solid/hollow resonator, Yan et al improved this to 25 deg/hr stability [2] at $\tau=0.1$ hr [11]. More recently, Suo et al [2] demonstrated the beneficial aspects of anti-resonant guiding HC, showing 0.15 deg/hr short-term ($\tau=200$sec) bias instability in a transmission-mode RFOG using Kagome HC. Our own observations of modal-purity problems in HC-PBGFs having nodal points, reports of higher backscatter (vs. solid single-mode fiber), and spurious glass-propagating modes in these fibers [12,13] led us to investigate an alternative HCF type.

Here we focus on Nested Anti-resonant Nodeless Fiber (NANF) [14], the structure of which is compared in Fig 2 to that of a more traditional HC-PBGF. In HC-PBGFs a lattice of glass nodes (the vertices of the hexagonal cells shown in Fig 2a) establishes an air-guiding bandgap in the core. However, the glass struts which are required to position these nodes at the correct locations in space increase the loss, reduce the bandwidth, and affect the modal and polarization properties of the fiber [15], as hinted by the irregular spatial arrangement of field contours near the core boundary in Fig 2a. Moreover, they support glass-propagating surface modes [15], which can contribute to RFOG drift. In contrast, for NANFs it is the struts themselves – in the form of the non-contacting, nested tubes (Fig 2b) – which confine light by coherent reflection. Only wavelengths which are resonant with the membrane thickness can couple out of the central void. States elsewhere in the spectrum are said to be in anti-resonance and are prevented from traversing the glass membranes in a manner akin to a Fabry-Pérot etalon.

Along with confinement, this mechanism produces an exceptionally low field overlap with the glass. For suitably designed NANFs, the total power propagating in the glass at anti-resonance varies from 10-60ppm, a factor of >10x less than in HC-PBGFs [15], thus reducing the fiber nonlinearity proportionally. Moreover, the field at the core boundary has excellent spatial regularity, with no surface modes and thus less polarization and spatial mode coupling [16]. Additionally, NANF cladding tubes can be designed to strongly attenuate all the air-guided higher-order modes (HOMs) of the core [17], rendering NANFs effectively single-mode after sufficient propagation length. Finally, NANFs have recently achieved the lowest loss of all HCF technologies (0.28 dB/km, [18]), and can be tailored for guidance in multiple spectral regions. This combination of ultra-low non-linearity, modal purity, and low loss promises to make NANFs an attractive enabler for RFOG.

2. Fiber Design & Performance

The two fibers tested in this work are depicted in Fig 3. Both are 6 nested tube designs with 33µm core diameters. The slightly non-uniform micro-structure of NANF 1 (Fig 3a) gives rise to a higher loss at 1550nm of 20 dB/km, while the more recently produced NANF 2 (Fig 3b) shows an improved symmetry and 2.8 dB/km loss. Both fibers were fabricated via a standard stack and draw process and they share similar design parameters with the low-loss (1.3 dB/km) NANF reported in [19]. The membrane thicknesses of NANF 1 and NANF 2 are 1.068 ± 0.061 µm (mean ± 1σ) and 1.22 ± 0.037 µm respectively.

One of the key challenges to HCF deployment in an RFOG lies in coherent backscattering. Judicious signal processing techniques can alleviate the primary error mechanisms that arise, but are unable to suppress secondary backscatter errors, including those mediated by surface modes in HC-PBGFs. Terrel et al [10], showed that HC-PBGF backscatter severely limits the bias instability of an HCF RFOG. There, the HC-PBGF coil showed a recaptured backscatter factor on the order
of $10^{-6}$ m$^{-1}$ – at least 25 times greater than that of solid-core SMF. Reflectometry measurements show that backscattering is dramatically reduced in NANFs, with the two fibers tested showing backscatter at least an order of magnitude lower than that of solid-core fiber. As shown in the high-resolution optical time domain reflectometry trace of Fig. 3c, NANF 2 has a backscattered power at or below the noise floor of the instrument, which is 12 dB below the Rayleigh scattering floor of SMF28. Only a few discrete peaks are visible in the trace, and even the worst of these is still ~5 dB lower than this solid fiber limit.

Fig. 3. Microstructure geometry and fiber-level performance. Optical microscope images of (a) NANF 1 and (b) NANF 2 (true-color images show illumination of the core region with white light), (c) Bi-directional reflectometry trace (OTDR) on NANF 2 at 1550 nm.

In NANF 1, cutback measurements using spatial and spectral imaging ("S" imaging [20]) indicate the least attenuated HOM, LP01, shows >1280 dB/km loss, and thus the highest HOM power after traversing the full coil is 160 dB below that of the fundamental. Bi-directional S" imaging on the full length of NANF 2 shows the presence of a modal coupling point ~25 m from the "A" side of the fiber, which we attribute to a localized scattering defect as this matches the reflective defect in the OTDR trace (Fig. 3c). Excluding this defect, for an optimized launch, all modal interferences are attenuated to below -85 dB, the noise floor of the measurement. This represents a remarkable improvement over HC-PBGFs, where discrete mode couplings are orders of magnitude larger, and in which surface mode interactions produce a persistent, distributed modal interference background [13].

3. RFOG Configuration & Performance

Both NANFs 1 and 2 were deployed in the experimental RFOG shown in Fig. 4. In the absence of suitable fiber couplers using HCF, free space optical lenses [1] were used to couple each end of the 136 m NANF coil to a first and second PM solid-core fiber coupler. The two PM couplers were then spliced together to close the resonator loop, and to provide means for coupling light into, and out of, the resonator. Inside each free-space portion of the resonator, a half-wave plate was used to align the optical polarization state to the principal axis of the fiber coil, and a polarizer was used to reduce polarization errors in the gyro [7]. The coil was wound around a 45-inch diameter cylinder. The coupling loss of each free-space to fibre coupling was approximately 665 dB, and for each leg, the 90/10 coupler split ratios resulted in a total resonator loss of 218 dB and a finesse of approximately 145. The CW and CCW resonances of the resonator were probed by lasers from a Multi-Frequency Laser Source (MFLS), having very low relative phase noise between CW and CCW input light. This technique [21], uses a master laser diode that is tightly locked to the CW resonance at the CW reflection port using a Pound Drever Hall (PDH) loop. Slave lasers 1 and 2 are phase-locked to the master laser, each with a tunable frequency offset that allows resonance tracking loops to adjust their optical carrier frequencies, at $f_{cw}$ and $f_{ccw}$, respectively, to the CW and CCW resonances. Light from slave lasers 1 and 2 is detected at CW and CCW transmission detectors after circulating within the resonator and being transmitted out of the resonator by an input/output coupler. Light emanating from each transmission port is directed to a transmission port detector via a circulator.

Fig. 4. (a) RFOG arrangement using NANF fiber for the resonator coil. (b) Drift-rate Allan Deviation of the RFOG plotted for 3 different resonator input optical power levels. The long-term bias instability for integration times of 1-10 hrs is roughly 0.05 deg/hr.
from a Royal Academy of Engineering Research Fellowship.

achievable through further optimization of the RFOG and this demonstrates performance which is within about 10x the requirement for subsequent embodiments. Nevertheless, this work demonstrates performance which is within about 10x the requirement for civil aircraft navigation usage, which we believe is realistically achievable through further optimization of the RFOG and this promising relatively young fiber technology.

Funding. This project has received funding from the European Research Council (ERC) (grant agreement n° 682724).

Acknowledgements. ENF gratefully acknowledges support from a Royal Academy of Engineering Research Fellowship.

Disclosures. The authors declare no conflicts of interest.

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