Measurement of reduced backscattering noise in laser-driven fiber optic gyroscopes

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We report what we believe to be the first demonstration of a laser-driven fiber optic gyroscope (FOG) built with an air-core fiber. Its phase noise is measured to be 130 μrad/$\sqrt{\text{Hz}}$. When the sensing fiber is replaced with a conventional fiber, this figure drops to 12 μrad/$\sqrt{\text{Hz}}$. Comparison between these values suggests that the air-core fiber gyro is most likely not limited solely by backscattering noise but by reflections at the solid-core/air-core interface. By minimizing additional noise sources and reducing the air-core fiber loss to its theoretical limit (~ 0.1 dB/km), we predict that the backscattering noise of the laser-driven air-core FOG will drop below the level of current FOGs. Compared with commercial FOGs, this FOG will exhibit a lower noise, improved thermal and mean-wavelength stability, and reduced magnetic-field sensitivity.

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The fiber-optic gyroscope (FOG) is a well-developed, highly stable, and sensitive device that has been commercially available for two decades. State-of-the-art sensors continue to be limited by three residual sources of error: thermal drift in the sensing fiber (Shupe effect), excess noise of the broadband light source used to interrogate the gyro, and mean-wavelength fluctuations of the source, which lead to errors in the scale factor. Since two of these issues stem from the use of a broadband light source, it is interesting to reexamine the possibility of replacing it with a laser. This option was abandoned more than two decades ago, because the use of a laser results in a strong Kerr-induced phase drift in the output signal, as well as a strong coherent backscattering noise [1]. Very little work has been done since then to investigate other solutions to these two problems. However, solutions do exist, in particular applying a square modulation to the input signal to eliminate the former [2], and applying a frequency modulation to reduce the latter [3]. In addition, we have shown that using an air-core photonic-bandgap fiber (PBF) in the sensing loop essentially eliminates the Kerr-induced drift (240-fold reduction has been demonstrated [4]) and greatly reduces the Shupe effect ($\sim$6.5-fold reduction [5]).

The only issue that remains to be solved to make a laser-driven FOG a reality, whether it uses a conventional or an air-core fiber, is coherent backscattering noise, which frequency modulation does not reduce sufficiently [6]. Reducing this noise to a manageable level would lead to a new generation of gyroscopes operated with a coherent source. Such a gyro would have reduced noise limited not by excess noise but by shot noise, with an extremely stable frequency and therefore scale factor, and an improved thermal stability in the case of a PBF FOG.

To make headway in this direction, we report what we believe to be the first measurement of the coherent-backscattering noise in a laser-driven FOG utilizing an air-core fiber (Crystal Fibre's 7-cell HC-1550-02 fiber [7]). With a laser linewidth of 200 kHz, we measured a phase noise of $\sim$130 μrad/$\sqrt{\text{Hz}}$. In the same FOG utilizing a conventional fiber (Corning's SMF-28 fiber) the measured noise level was 12 μrad/$\sqrt{\text{Hz}}$, i.e., $\sim$11 times lower. This last value is only a factor of 7 higher than the noise in the same FOG interrogated with a broadband light source. Comparison of these figures to the backscattering coefficient of each fiber suggests that the noise in the air-core FOG is not limited by backscattering solely but by additional noise sources in the loop, primarily reflections at the solid-core/air-core interface.

The FOG uses a Sagnac interferometer made of a coiled loop of either single-mode or air-core fiber (see Fig. 1). Light is split by a 3 dB coupler and coupled into the fiber coil in both the clockwise (cw) and counterclockwise (ccw) directions. After traversing the loop, the cw and ccw signals are combined at the coupler and interfere. Through the well-known Sagnac effect, this interference yields an output signal power that depends on the rotation rate imparted to the coil. Rayleigh scattering in the coil fiber gives rise to cw- and ccw-traveling backscattered signals. When using laser light with a coherence length of the order of the loop length, the backscattered fields produced by all of the scatterers in the sensing fiber interfere coherently with the primary cw and ccw signals, generating an unacceptably strong coherent-backscattering phase noise [1].

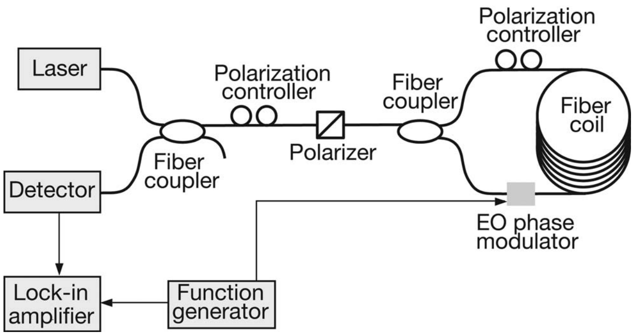

Fig. 1. Experimental laser-driven fiber optic gyroscope.

The only published model of backscattering phase noise (to our knowledge) in a FOG operated with a light source with a coherence length L_c approximately equal to the loop length L predicts that the maximum value of this noise is given by [1]

$$\phi_n \approx 2\sqrt{\alpha_b L}, \tag{1}$$

where α_b is the intensity backscattering coefficient of the fiber. However, this model assumed a worst-case scenario in which all the scattered fields add constructively with the primary signals. In reality, there is some randomness to the phase of the scattered photons, so this model strongly overestimates the noise. Other published theoretical simulations of backscattering noise in a FOG assume that L_c is much smaller than L [8,9]. Until a more advanced model is developed, we are therefore unable to make accurate quantitative predictions of the backscattering noise in our FOG. However, the derivation of (1) in [1] suggests that even after taking into account the random phase of the scattered signals, it is reasonable to expect that the noise will still vary approximately like the square root of the backscattering coefficient. This assumption makes it possible to compare, at least qualitatively, the relative noise of our two gyros.

For most fibers, the backscattering coefficient can be measured directly using either time- or frequency-domain reflectometry. In a standard single-mode fiber, the predominant source of backscattering is Rayleigh scattering. From the published data sheet for Corning SMF-28 fiber, the Rayleigh backscatter coefficient is expected to be 82 dB in a 1 ns pulse width [10], which corresponds to $\alpha_{b,SMF\text{-}28} = 6.2 \times 10^{-8}\ \mathrm{m}^{-1}$.

Backscattering in an air-core fiber arises from at least two mechanisms. The first one is Rayleigh scattering from the silica membranes of the photonic crystal (Rayleigh scattering from the air is negligible). Based on the very small fraction of the fundamental mode energy located in these membranes ($<1\%$), this component is expected to be quite small. The second mechanism is mode coupling caused by random perturbations of the transverse dimensions of the fiber core region. Given the comparatively high loss of our air-core fiber (~ 24 dB/km), this contribution is expected to dominate and to be significantly larger than in a conventional fiber. A recent model of this mechanism has shown that the backscattering coefficient should be $1.5 \times 10^{-6}\ \mathrm{m}^{-1}$ [11]. This prediction is supported by the one and only reported measurement of backscattering in an air-core fiber [12]. Although no *absolute* value of the backscattering coefficient for the air-core fiber was listed in [12], straightforward analysis of the data (Fig. 3 of [12]) yields a value of $1.58 \times 10^{-6}\ \mathrm{m}^{-1}$, which was confirmed by one of the authors [13]. This is in agreement with our own measurement in our 235 m coil of air-core fiber using a high-resolution reflectometer from Luna Technologies (OBR™ 4400), which gave $\sim 1.5 \times 10^{-6}\ \mathrm{m}^{-1}$. The backscattering coefficient of our air-core fiber loop is therefore expected to be $\alpha_{b,PBF} \approx 1.5 \times 10^{-6}\ \mathrm{m}^{-1}$, or roughly 24 times higher than the SMF-28 fiber's. Everything else being the same, the laser-driven FOG is therefore expected to have $\sim \sqrt{24} \approx 4.9$ times higher noise with our air-core fiber than with an SMF-28 fiber.

The configuration of the SMF-28 fiber gyro is shown in Fig. 1. The sensing coil consisted of 230 m of SMF-28 fiber quadrupolar-wound on a mandrel of diameter $D = 8$ cm. The phase modulation was provided by an electro-optic phase modulator driven sinusoidally at the proper loop frequency $f_0 = 435$ kHz. The detected signal at f_0 was filtered through a lock-in amplifier with an equivalent bandwidth of 8 Hz. The modulation amplitude was selected to maximize the response to rotation. A polarizer was placed before the loop to guarantee polarization reciprocity. A first polarization controller (PC) was inserted just before it to maximize the power launched into the loop, and a second one inside the loop to maximize the power returning to the detector. The source was a 1550 nm semiconductor external-cavity laser (ECL-210 manufactured by Santec) with a linewidth of 200 kHz (coherence length in SMF-28 fiber of ~ 325 m). The power returning to the detector was 10 μW.

In the absence of rotation, we measured the demodulated signal returning from this gyro. The results are shown in Fig. 2, where the lock-in amplifier's output voltage is plotted over a period of 10 s with an effective integration time of 0.13 s. The standard deviation of this signal provides the noise of the gyro, in volts. To calibrate this voltage noise into a phase noise, we applied to the gyro a small known rotation rate. Using the gyroscope's known scale factor (0.25 s), the output phase shift resulting from this rotation was calculated and then compared with the measured rotation-induced voltage. When the FOG was interrogated by the laser, the phase noise measured from this curve was 12 μrad/$\sqrt{\text{Hz}}$. For comparison, when the same FOG was interrogated with a broadband Er-doped superfluorescent fiber source (SFS), at the same returning power the measured phase noise was only 1.7 μrad/$\sqrt{\text{Hz}}$. Using the laser instead of the SFS therefore increased the noise by a factor of ~ 7. The noise measured with the laser is nearly 450 times lower than the worst-case value predicted from [1]. This constitutes the first (to our knowledge) demonstration that a conventional FOG can be operated with a laser yet exhibit a noise only seven times higher than when operated with a broadband source.

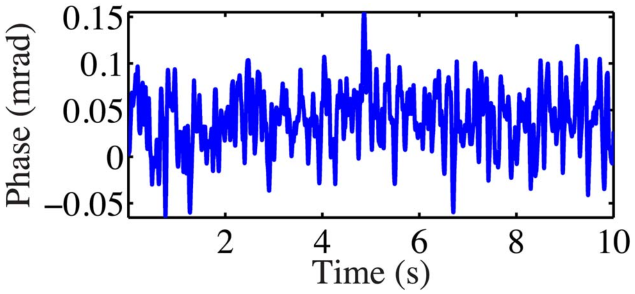

Fig. 2. (Color online) Typical output of the laser-driven SMF-28 fiber optic gyroscope under constant rotation.

The laser-driven air-core FOG had the same configuration as Fig. 1, except that (1) the sensing coil used 235 m of HC-1550-02 air-core fiber, (2) the two fiber ends were buttcoupled to the pigtails of the 3 dB coupler (normal cleaves), and (3) the phase modulator was driven at the proper frequency for this loop (635 kHz). The phase noise measured for this gyro is shown in Fig. 3. This curve yielded a phase noise of 130 μrad/$\sqrt{\text{Hz}}$, or ~11 times higher than with the SMF-28 fiber coil. When the laser was replaced by the SFS, it decreased to 2.9 μrad/$\sqrt{\text{Hz}}$. Note that owing to the high fiber loss, the returning power with the laser was only 5 μW instead of 10 μW.

The result with the SFS-driven air-core FOG makes sense: the measured phase noise is approximately the same with either fiber type. This is because the noise is imposed by the source excess noise [14], which is the same in both FOGs. When the broadband source is replaced with a laser, the phase noise is expectedly higher with the air-core fiber because of its higher backscattering coefficient. However, as discussed earlier, from the known backscattering coefficients of the two fibers we anticipated a ratio of backscattering noise of ~4.9. The much higher measured ratio (~11) indicates that the noise of our laser-driven air-core FOG is not limited by backscattering but by additional sources. One likely source is coherent reflections at the two interfaces between the solid-core and air-core fibers in the loop. Such small reflections create a spurious Mach–Zehnder interferometer with the primary signal. Owing to the high coherence of the source, the significant propagation loss in the coil, and the extremely large and unstable path difference between the two arms, this interference can lead to large fluctuations in the output signal, which could well account for the increase in measured noise.

We are in the process of investigating methods for reducing these spurious reflections. This work shows that even after this step is completed, the backscattering noise with a laser source will still be higher than the excess noise of a typical broadband source, and that it will need to be reduced. A first method is modulating the laser frequency, as was demonstrated in [6]. A second method is reducing the air-core fiber loss from its current 24 dB/km to its lowest theoretical value of ~0.1 dB/km [15]. Experimentally measured losses as low as 1.2 dB/km have already been published [15]. If one assumes that the backscattering in an air-core fiber is proportional to the loss, a lower loss air-core fiber coil in conjunction with frequency modulation of the source is expected to lower the noise of the air-core FOG to the level of a conventional FOG operated with a broadband source.

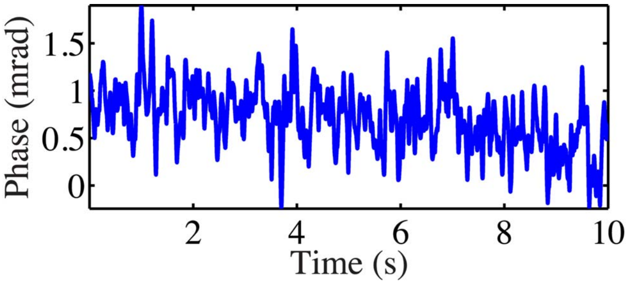

Fig. 3. (Color online) Typical output of the laser-driven air-core fiber optic gyroscope under constant rotation.

In summary, we have demonstrated that an experimental FOG made with conventional fiber and driven by a laser exhibits a coherent-backscattering phase noise of only 12 μrad/$\sqrt{\text{Hz}}$. This low noise points for the first time (to our knowledge) to new prospects for operating a conventional FOG with a laser. When used with an air-core fiber, this same gyro exhibited a phase noise of 130 μrad/$\sqrt{\text{Hz}}$. Comparing the backscattering coefficients of these two fibers, these results suggest that the noise of the air-core FOG is not limited by backscattering noise. The most likely dominant source of noise is coherent reflections from the connections between dissimilar fibers inside the sensing coil. By eliminating these reflections, and implementing two proven techniques for reducing backscattering noise, this work suggests that the noise of the air-core FOG can be brought down to the noise level of a conventional FOG operated with a broadband source. This achievement would come with the significant additional benefits of reduced thermal sensitivity and improved scale factor stability.

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