A Large Area Fiber Optic Gyroscope on multiplexed fiber network

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We describe a fiber optic gyroscope based on the Sagnac effect, realized on a multiplexed telecom fiber network. Our loop encloses an area of 20 km^2 and coexists with Internet data traffic. This Sagnac interferometer is capable of detecting signals that are larger than 10^{-8} (rad/s)/$\sqrt{\mathrm{Hz}}$, thus approaching ring laser gyroscopes without using narrow-linewidth laser nor sophisticated optics. The proposed gyroscope could be useful for seismic applications, opening new possibilities for this kind of optical fiber sensors.

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Optical sensing of ground rotations induced by earthquakes has been demonstrated with optical gyroscopes exploiting the Sagnac effect [1–3]. These instruments are very promising for understanding ground motion, as they are not sensitive to translational motion, and field deployable rotation sensors based on the Sagnac effect have begun to be developed as a result [4]. Ring Laser Gyroscopes (RLGs) can detect rotation signals lower than 10^{-9} (rad/s)/$\sqrt{\mathrm{Hz}}$ [2, 5, 6]; however they are not well suited for commercial implementation, as they require careful maintenance and sophisticated instrumentation. On the other hand, rotation sensors based on passive Fiber Optic Gyroscopes (FOGs) have a broader dynamic range, are transportable, and require only commercial components [7, 8]. However, ordinary FOGs are limited by shot noise, and not sensitive enough to measure rotational signals from distant earthquakes [4]: their sensitivity limit typically ranges around $10^{-4} - 10^{-6}$ rad/s, with a single more relevant result in the 10^{-8} rad/s range [9].

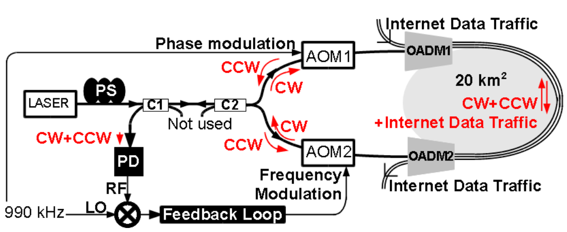

Fig. 1. Setup of our FOG: PS polarization scrambler, C couplers, CW(CCW) clockwise(counterclockwise) laser beam, AOM acousto-optic modulators, OADM Optical Add and Drop Multiplexers, PD photodiode.

To exploit the advantages of FOGs while overcoming their sensitivity limitation, we realized a fiber gyroscope on a multiplexed telecom fiber enclosing a large urban area. The proposed Sagnac interferometer can detect variations of the rotation rate larger than 10^{-8} (rad/s)/$\sqrt{\mathrm{Hz}}$. The setup is simple, uses off-the-shelf components and can be run on any fiber loop enclosing an area. Therefore, devices such this one can be suitable for a distributed grid covering a wide region.

In this Letter we present the detailed setup of our FOG, the results in terms of rotational sensitivity, an analysis of the present limitations and a comparison with state-of-the-art RLGs. Then, we point out the possible use of this optical fiber sensor for seismic applications.

In a Sagnac interferometer two laser beams counter propagate in an optical fiber loop enclosing an area, and accumulate a non-reciprocal phase shift [7]:

$$\varphi_{\mathrm{nr}} = \frac{8\pi\nu}{c^2}\mathbf{A}\cdot\mathbf{\Omega}, \tag{1}$$

where ν is the laser frequency, c is the speed of light in vacuum, $\mathbf{A}$ the area enclosed by the loop, and $\mathbf{\Omega}$ the rotation rate of the FOG reference frame.

Our interferometer is composed by a 47 km single mode commercial fiber located in the urban area around the city of Turin (Italy, colatitude 45°). Its shape is an elongated triangle with an enclosed area of 20 km^2. The resulting phase due to the Earth rotation is thus estimated to be about 55 rad. In fact, the present experiment aims not to detect the accurate value of this phase but its variations. The optical fiber is used for the Internet data traffic and is implemented on a Dense Wavelength Division Multiplexed (DWDM) architecture, with ∼23 dB of optical losses. The optical source is a laser radiation at 1542 nm provided by a fiber laser of about 10 kHz linewidth, described in [10], corresponding to the 44th channel of the International Telecommunication Union (ITU) grid, while Internet data are transmitted on the 21st and 22nd channel, 2 THz away. There is no evidence of crosstalk between the channels. In Figure 1 the experimental setup is shown, in a minimum configuration scheme: laser radiation is injected in the interferometer and split into two beams travelling over the loop in opposite directions, the first clockwise (CW), and the second counterclockwise (CCW). The setup design assures that the two beams travel exactly the same fiber. The polarization of the injected light is randomized through a polarization scrambler PS; this reduces the effect of polarization mode dispersion along the fiber, i. e. a source of phase shifts between the two beams. Before being coupled into the urban fiber loop, the two beams are frequency shifted by 40 MHz with two acousto-optic modulators (AOMs). AOM1 also modulates the phase of the optical carrier at a rate of $f_\mathrm{m} = 990\,\mathrm{kHz}$: the CW beam is thus phase modulated immediately at the beginning of the loop, whereas the CCW beam is modulated after a round trip. The two beams, with optical power of 3 mW each, are injected in the telecom fiber using the Optical Add and Drop Multiplexers OADM1 and OADM2. While travelling over the loop, they accumulate a phase difference φ_nr due to the Sagnac effect. After a round trip, they are extracted and recombined on the photodiode PD. Since there is a time delay τ=235 µs between the phase modulation of the two beams, the current from the photodiode also varies at the phase modulation rate f_m. It can be expressed in the form [11]:

$$I = I_0 + I_1 J_1(x)\sin\varphi_\mathrm{nr}\cos\left[2\pi f_\mathrm{m}\big(t-\frac{\tau}{2}\big)\right] + \\ + f_\mathrm{m}\ \text{harmonics} \quad (2)$$

I_0 and I_1 are respectively the amplitudes of the dc and the first harmonic signal and depend on the optical power of the beams, J_1 is the first Bessel function of the first kind, $x = 2\phi_0\sin(2\pi f_\mathrm{m}\tau)$, and ϕ_0 is the phase deviation depth. f_m and ϕ_0 are set to maximize the first harmonic term. This signal is processed to extract φ_nr. We set up a closed-loop system, in which φ_nr is compensated by a frequency offset Δ_f between the two beams [11]. When the loop is closed, Δ_f satisfies the relation:

$$\varphi_\mathrm{nr} \pm 2\pi k = 2\pi(nL/c)\Delta_f \quad (3)$$

where n is the refractive index of the optical fiber, L the loop length, and k is an integer responsible for a 2π ambiguity in the recorded phase. AOM2 is used as the actuator of the feedback loop. Δ_f is set below 2 kHz to reduce the sensitivity on optical path length variations $\delta(nL)$, that can induce a non-reciprocal phase $\varphi = (2\pi/c)\Delta_f\delta(nL)$. Assuming that φ_nr is only due to the Sagnac effect, from eq. (1) and eq. (3):

$$\Delta_f = \frac{4\nu}{nLc}\mathbf{A}\cdot\mathbf{\Omega} \quad (4)$$

Thus, the correction frequency Δ_f can be recorded to extract information about variations of Ω. This formula is the same as for RLGs, but the derivation is independent.

The noise power spectral density (PSD) of Δ_f, that is proportional to φ_nr through eq. (3), was acquired with a Fast Fourier Transform Spectrum Analyzer and is shown in Figure 2 (left-hand axis). This signal was converted into variations of the Earth rotation rate using eq. (4); the scaled result is shown on the right-hand axis. The Sagnac phase shift depends in principle on tilt variations (change in $\mathbf{\Omega}/\Omega$) and spin variations (change in Ω); however, the sensitivity to variations of tilt is about $\sim 10^4$ times lower than the sensitivity to variations of spin. Figure 2 (right-hand axis) also shows the present sensitivity limit of this FOG, and, for comparison, the noise of three RLGs: G-Pisa, in Italy [2], UG-II, in New Zealand [5], and G, in Germany [6].

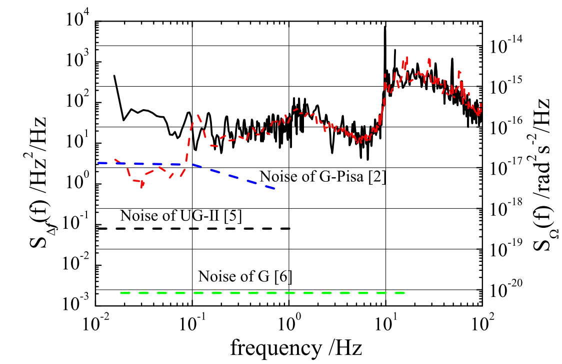

Fig. 2. PSD of the correction frequency Δ_f (black solid line, left-hand axis) and equivalent spin variations (right-hand axis). Red line: contribution from fiber's mechanical noise; dashed lines (right-hand axis): noise of G-Pisa (blue) [2], UG-II (black) [5], G (green) [6].

The sensitivity of our setup is mainly limited by seismic noise, acoustic vibrations on the buried fiber induced by human activity, and asymmetrical temperature variations. These effects induce a phase noise $S_{\varphi_\mathrm{F}}(f)$ on the optical carrier [12]; at first order, our interferometer is insensitive to them, as CW and CCW beams travel in the same fiber. However, since they travel in opposite directions, the uncorrelated residual optical length variation leads to phase fluctuations. Following an approach similar to [12], we can calculate this contribution to be

$$S_{\varphi_\mathrm{F,NR}}(f) = \frac{1}{3}(2\pi f\tau)^2 S_{\varphi_\mathrm{F}}(f) \quad (5)$$

$S_{\varphi_\mathrm{F}}(f)$ was estimated from previous measurements on the fiber loop used [13] and it is the ultimate limitation to the sensitivity of our FOG. Figure 2 shows its equivalent contribution in terms of Δ_f (red line, left-hand axis). This noise merely depends on the loop length: thus for a given fiber length, it is beneficial to maximize the enclosed area. For instance, in our configuration, keeping the same 20 km^2 area, the sensitivity could have been improved of a factor ~ 26 if the loop had not been an elongated triangle but a circle (i.e. 15.8 km length). In addition, $S_{\varphi_\mathrm{F}}(f)$ scales as L and $S_{\varphi_\mathrm{F,NR}}(f)$ scales as L^3 [12], whereas the Sagnac phase power spectral density scales as $A^2 \sim L^4$, thus the noise could be further reduced for fiber loops enclosing a wider area.

Other noise contributions could come from the Kerr effect, backscattering, and scale factor instability, i.e. variations in the area A or length L. The phase dependence on the optical power as predicted by the Kerr effect [14] was assessed changing the optical power of the CW beam with respect to the CCW. Even with a power unbalance of 20% Kerr related effects were not detected, so this contribution is negligible for optical power fluctuations in normal operation, i. e. less than 5%. To investigate the effect of backscattering, we changed the frequency offset between the two AOMs. The backscattered signal passes two times in AOM1 or in AOM2. Thus, it could be set at the same frequency of the coherent beatnote, or at about 200 kHz separation and filtered out. We did not detect any difference in the two configurations, so we conclude that this contribution is below the noise. Concerning the scale factor instability, the sensitivity of our setup to length variations is 0.8 Hz/m, whilst the sensitivity to area variations is 2×10^{-3} Hz/m^2. Thus, for any reasonable change in L or A, these contributions are below the present noise.

The instability over long measuring times has been evaluated through the Allan deviation $\sigma_{\Delta_f}(\tau)$ of Δ_f as a function of the averaging time τ. This is shown in Figure 3 together with the Allan deviation of the corresponding rotation signal $\sigma_\Omega(\tau)$. The excess of instability

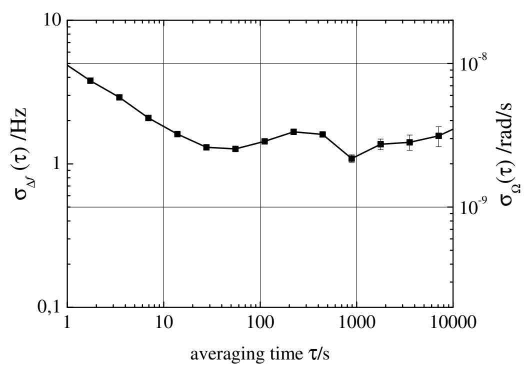

Fig. 3. Allan deviation of the correction frequency $\sigma_{\Delta_f}(\tau)$ (left-hand y axis) and the equivalent instability $\sigma_\Omega(\tau)$ of the spin variations (right-hand y axis).

on timescales longer than 100 s is due to polarization drifts that make our system sensitive to the fiber linear and circular birefringence (for instance, due to stresses or Faraday effect [15]). These effects could be reduced by improving the depolarization stage and by using an optical source with larger linewidth [8].

In conclusion, we demonstrated that ordinary fiber networks, used for Internet data traffic, could be exploited to implement optical rotation sensors based on the Sagnac effect. This experiment could pave the way for a network of these sensors for seismic detection, placed side by side with traditional instrumentation, and supported by the increasing activity on fiber networks for frequency metrology [16, 17, and refs. therein]. The advantage of the proposed setup is a good sensitivity, obtained using wide infrastructures already commercially available, such as the fiber networks, without sophisticated setup. The sensitivity is not yet fully exploited, and improvements beyond the demonstrated performances are feasible. This type of rotation sensor could offer new opportunities for detection of seismic events, provided a deeper investigation on some issues. These include: a better understanding on how the ground motion is detected by a large-area sensor, and the feasibility of a real distributed grid of gyroscopes. These issues are currently under study.

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