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A test resonator for Kagome Hollow-core Photonic Crystal Fibers for resonant rotation sensing

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ABSTRACT

We build ring resonators to assess the potentialities of Kagome Hollow-Core Photonic Crystal Fibers for future applications to resonant rotation sensing. The large mode diameter of Kagome fibers permits to reduce the free space fiber-to-fiber coupling losses, leading to cavities with finesses of about 30 for a diameter equal to 15 cm. Resonance linewidths of 3.2 MHz with contrasts as large as 89% are obtained. Comparison with 7-cell photonic band gap (PBG) fiber leads to better finesse and contrast with Kagome fiber. Resonators based on such fibers are compatible with the angular random walk required for medium to high performance rotation sensing. The small amount of light propagating in silica should also permit to further reduce the Kerr-induced non-reciprocity by at least three orders of magnitudes in 7-cell Kagome fiber compared with 7-cell PBG fiber.

1. Introduction

Recent progresses in hollow-core photonic crystal fibers (HC-PCF) and compact single frequency laser sources renewed interest for the resonant fiber optic gyroscope (R-FOG). The basic principle of an R-FOG is to measure, by using an external probe laser, the eigenfrequencies of two counter-propagating modes of a fiber ring cavity, their difference being proportional to the angular velocity of the device (Sagnac effect). Unlike the interferometric fiber optic gyroscope, which requires several hundreds of meters of fiber to reach the required sensitivity for inertial navigation, here, only a very short length (few tens of cm to few meters) of optical fiber is sufficient. While the first proof-of-principle of an R-FOG was made as early as 1983 [1], its impact on applications remained limited owing to several reasons such as high level of Kerr induced bias instabilities in solid-core fibers.

The breakthrough of using bandgap guidance to trap light in a low-index core makes HC-PCFs promising candidates for building medium to high grade gyroscopes [2]. Hollow-core (HC) fibers, where light propagates mostly in air, have the advantage of significantly reducing the Kerr effect, known as a strong limitation on the bias stability of the R-FOG [3]. These fibers exhibit reduced bulk scattering and detrimental effects (thermal fluctuations, mechanical stress and radiation effects) that create noise and dissipate signals [4,5], although new problems emerge due to surface scattering [2,6]. A first demonstration of a R-FOG using a 7-cell core hollow-core photonic band gap (PBG) fiber has been published by Terrel et al. [2]. The achieved performances (bias stability around 1 deg/s) are still several orders of magnitude poorer than the one typical required for inertial navigation. Recently, Qiu et al. [7] have reported a R-FOG based on standard PM fiber with a laser stabilized to an external resonator. The bias stability and angular random walk were 0.1 deg/h and $0.008\ \text{deg}/\sqrt{\text{hr}}$, respectively. These interesting results are a promising sign that commercial R-FOG with navigation or tactical grade performance might be attainable in the near future.

The HC fibers investigated here are based on a Kagome lattice design. Unlike PBG guiding fibers, photons are confined inside Kagome HC fibers not by PBG but via a mechanism akin to Von Neumann-Wigner bound states in a continuum, and whereby the fiber guided modes cohabitate with those of the cladding without notably interacting. This inhibited coupling between the propagation mode and the surrounding silica cladding is explained by the large transverse spatial-phase mismatch between the core and the cladding fields. The mode power fraction propagating in glass is reported to be below 0.05% [8,9], which is about two orders of magnitude lower compared to typical values (few percents) for

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PBG fibers. As a result of this weak interaction between the core and cladding modes, Kagome HC-PCFs exhibit broad transmission regions with relatively low loss covering the spectral range from IR to UV, and open new potentialities for many applications [10,11], in particular for rotation sensing with a weak Kerr effect, and potential reduction of backscattering [2].

In this paper, we present experimental results on an Inhibited-Coupling (IC) guiding Kagome HC-PCF based resonators. In particular, by using a simple semi-bulk cavity design, we build test resonators that allow us to characterize and investigate different HC fibers and to compare their performances in terms of cavity linewidth and fraction of intensity in silica, for gyroscope application. Two figures of merit are defined to evaluate them.

2. Fundamental limits in R-FOGs

Ultimately, if we assume that all effects related to laser noise, backscattering, mechanical and thermal drifts, etc. are avoided, the noise performance of the R-FOG is limited by the shot-noise limit (SNL). The latter can be made in principle arbitrarily small by increasing the intra-cavity power, but this will in return increase non-linear effects within the fiber, such as Kerr effect, leading to bias instaility. Consequently, the maximum achievable signal-to-noise ratio will be a trade-off between increasing the circulating power and minimizing the nonlinear effects. In this section, we express the driving parameters to obtain this trade-off for the case of hollow-core fibers.

2.1. Shot-noise sensitivity limit

The frequency difference Δf between the two counter-propagating modes of the R-FOG cavity is given by:

$$\Delta f = \frac{4A}{\lambda L}\dot{\theta}, \tag{1}$$

where A is the area enclosed by the cavity and L its optical perimeter, while λ and $\dot{\theta}$ are the light wavelength and the rotation rate, respectively. We note here that the scale factor is directly proportional to the ratio A/L, and thus cannot be increased by multiplying the number of fiber turns in the cavity, contrary to what happens in interferometric fiber optic gyros [12]. Thus, for simplicity, we replace A/L by $D/4$, where D is the diameter of the equivalent circular cavity. For a rotation measurement involving N_{pH} photons, the minimum measurable rotation rate $\dot{\theta}_{min}$ is:

$$\dot{\theta}_{min} = \frac{\lambda L}{4A}\delta f_{min} = \frac{\lambda}{D}\frac{\Gamma}{\sqrt{\alpha N_{pH}}}, \tag{2}$$

where δf_{min} is the minimum measurable value of the frequency difference Δf, Γ and α are respectively the cavity resonance linewidth and contrast. This contrast, which is between 0 and 1, is defined as $(I_{max} - I_{min})/I_{max}$, where I_{max} and I_{min} are respectively the maximum and minimum intensities for the considered transmission or reflection resonance. The number of photons used for the measurement can be related to the detected optical power P_{det} and the measurement time T by $N_{pH} = P_{det}T/(hc/\lambda)$, so that the expression of the angular random walk (ARW) is [12]:

$$ARW = \dot{\theta}_{min}\sqrt{T} = \frac{\Gamma}{D}\sqrt{\frac{hc\lambda}{\alpha P_{det}}}. \tag{3}$$

This equation shows that the ARW can be minimized by increasing the contrast and decreasing the linewidth of the cavity. This leads to define a cavity figure of merit FOM_{SNL} for the shot noise limit:

Table 1
Typical values of Kerr effect for different types of fibers.

Fiber	η	MFD	$\Delta P/P$ for 0.001°/h bias
SMF 28	1.0	10 μm	$\simeq 9 \times 10^{-6}$
HC PBG	0.05	10 μm	$\simeq 1 \times 10^{-4}$
HC Kagome	0.0004	40 μm	$\simeq 0.2$

$$FOM_{SNL} = \frac{\sqrt{\alpha}}{\Gamma}. \tag{4}$$

This figure of merit permits to compare the different fibers, even if a maximum contrast is not always optimal for sensitivity to rotation. It is also worth noticing that the finesse of the cavity is not the relevant figure of merit to discuss the sensitivity to rotation.

2.2. Kerr effect

For given figure of merit (Eq. (4)), cavity diameter D, and wavelength λ, the only way to improve the ultimate performance of an R-FOG is to increase the optical power launched inside the cavity. However, this increases the Kerr effect in the fiber, which turns out to be an important source of bias for the R-FOG, as discussed below.

In the presence of an intensity I, the refractive index n of silica evolves according to $n = n_0 + n_2 I$, where n_0 is the linear refractive index and n_2 is the nonlinear refractive index coefficient. This results in two different nonlinear refractive indices if the two counter-propagating fields inside the fiber cavity have a power difference ΔP, inducing the following bias for the optical gyroscope [13]:

$$\Delta\dot{\theta} = \frac{cn_2}{Dn_0}\frac{\Delta P\eta}{\sigma}, \tag{5}$$

where σ is the effective area of the guided mode and η the fraction of the mode power which is propagating in silica. Table 1 gives the maximum values of the relative power difference $\Delta P/P$ (for $P = 1$ mW inside the cavity) to achieve a bias $\Delta\dot{\theta} < 0.001$ °/hr, a typical value for a high performance grade gyroscope, calculated for three different fibers: standard telecom fiber, HC PBG fiber, and HC Kagome fiber. These calculations were performed for $D = 15$ cm and $n_2 = 3.0 \times 10^{-20}$ m^2/W for silica. The value of η for the Kagome fiber at 1.5 μm is taken from [8]. The refractive index for SMF 28 fiber is taken equal to 1.5. The values used for MFDs and η in HC PBG and HC Kagome fibers in Table 1 are just typical orders of magnitudes. The precise values of these parameters depend on the details of the design of the fibers, as will be described below (see Table 2) for the fibers we actually used in our experiments.

HC PBG fibers lead to a significant reduction of Kerr effect with respect to standard SMF fiber. However, we can see that for the Kagome fiber, which presents the largest mode field diameter and the lowest mode power fraction inside silica, the bias of the R-FOG becomes almost insensitive to any power difference between the two counter propagating beams. Differently, when the mode field

Table 2
Properties of the fibers tested here.

Fiber	Length (m)	Losses (dB/km)	MFD (μm)	η (%)	$\frac{P_{out}}{P_{in}}$ (%)
Kagome A	2.4	80	40	5.0×10^{-2}	91
Kagome B	2.3	60	34	2.0×10^{-3}	85
7-cell PBG	19	22	7.7	6	70