Hollow Core Fibers for Fiber Optic Gyroscopes

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Gyroscopes for rotation sensing are based on several design platforms, each with their advantages and disadvantages, depending on the application. Advancements in optical fibers have enabled the fiber optic gyroscope (FOG) to become an attractive choice for demanding applications. As this design platform matures, it can benefit from further advancements in optical fiber design. In particular, a relatively new type of optical fiber with a hollow core allows light signals to propagate mainly in air and overcome many of the limitations of conventional silica core fibers. For FOGs, compared to conventional fibers, this can mean:

Improved packaging
- ***Reduced form factor enabled by small coiling diameter 6x tighter than conventional fibers***
- ***Low magnetic field sensitivity requires less shielding***
- ***Index match to air enables low reflectance free space coupling***

Improved stability (less drift)
- ***Low optical nonlinearities***
- ***7x lower temperature sensitivity (Shupe effect)***
- ***50x lower radiation sensitivity***

The following provides a brief background and description of FOGs, with a focus on the key optical fiber properties and requirements. It also identifies areas where continued development of hollow core fibers offer the opportunity to further advance the technology and fully realize the benefits in advanced FOG applications.

Technology platforms for gyroscopes

Gyroscopes are used for a variety of applications from lower end commercial and industrial applications to more demanding high end applications such as aircraft and spacecraft navigation. The requirements will largely depend on the application, and various design platforms are addressing these, with four common platforms including mechanical, ring laser, micro-electro-mechanical system (MEMs), and fiber optic gyroscopes.

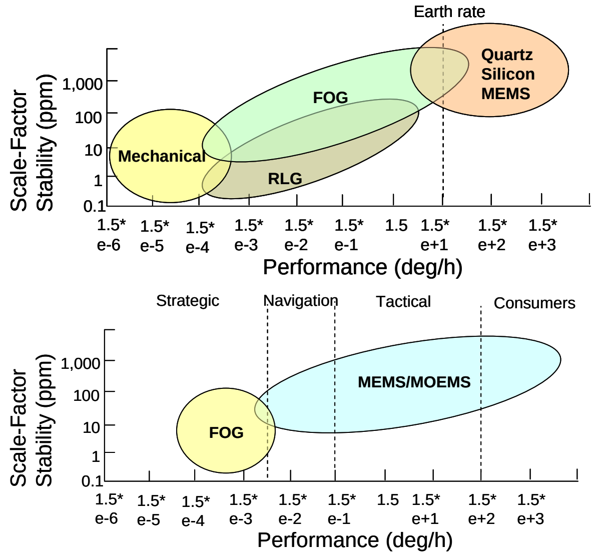

Figure 1. Near-term technology applications based on current gyros (top), and far-term applications (bottom)
Figure from: N. Barbour, and G. Schmidt, "Inertial sensor technology trends," IEEE Sensors Journal, Vol. 1, No. 4, 2001.

While mechanical gyroscopes have dominated the high end application space, these can suffer from their high cost, large size, weight, power consumption, and their reliance on moving parts which compromises stability and reliability. Ring laser gyroscopes improve on size, but can still be relatively large and costly. On the lower end of the application space, MEMS gyroscopes offer a path toward low cost, but do not offer the performance needed for higher end applications. The fiber optic gyroscope offers high performance, reduced size and weight, high reliability (no moving parts and a high resistance to shock and vibration), and low power consumption. Figure 1 offers a view of these technology platforms for the various application spaces and performance requirements, and projects that the FOG will displace mechanical and ring laser gyroscopes in the future.

The FOG operating principle

Similar to ring laser gyroscopes, the FOG is based on the Sagnac effect. In the FOG, a length of optical fiber is set up as a ring interferometer, as shown in Figure 2. A signal is launched into the fiber in both directions of the loop, i.e., clockwise (CW) and counterclockwise (CCW), where the optical path length would nominally be the same; however, the Sagnac effect results in a difference in the optical path lengths when the system undergoes rotation. By detecting the two signals on the receive end and combining them, the interference and corresponding phase shift can be related to an angular rotation. In a real system, changing conditions and design limitations can compromise the performance of the system such that noise and other detrimental factors lead to reduced precision and accuracy, and increased drift.

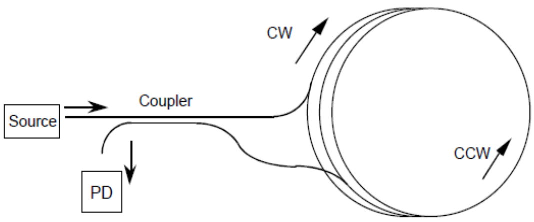

Figure 2. Basic principle of FOG. Figure from: Fiber Gyroscope Principles, SABINA MERLO et. Al., Electrooptics Group, University of Pavia, Italy, Chapter 16 in HANDBOOK OF FIBRE OPTIC SENSING TECHNOLOGY (from web)

Types of FOGs

Two commonly referenced FOG types are the interferometric fiber optic gyroscope (IFOG) and the resonator fiber optic gyroscope (RFOG) as shown in Figure 3.

IFOG

The IFOG is a relatively mature design and includes a coil of fiber that can be hundreds or thousands of meters in length. In general, the performance will improve with increased optical path length (fiber length), but a balance must be struck with regard to optical budget, packaging and cost. In the IFOG configuration, the CW and CCW signals make a single pass through the length of the fiber.

RFOG

In contrast, the RFOG may use up to 100 times less fiber length, but achieves an effectively long optical path length by recirculating the signal through multiple passes of the coiled fiber. The Fresnel reflection makes this configuration difficult using conventional fibers due to the loss each time light exits / enters the optical fiber.

In either case, the properties of the optical fiber can play a large role in determining gyroscope performance.

Of course, there are many other key components and design choices in a FOG. One that is strongly related to the optical system is the choice of optical signal source, which may be a broadband source with a short coherence length or a highly coherent narrowband source. The broadband source, although typically higher in cost, can help mitigate some of the limiting factors in the optical system. Beyond this, there may be other optical components, integrated circuits, mechanical features, software, and others that

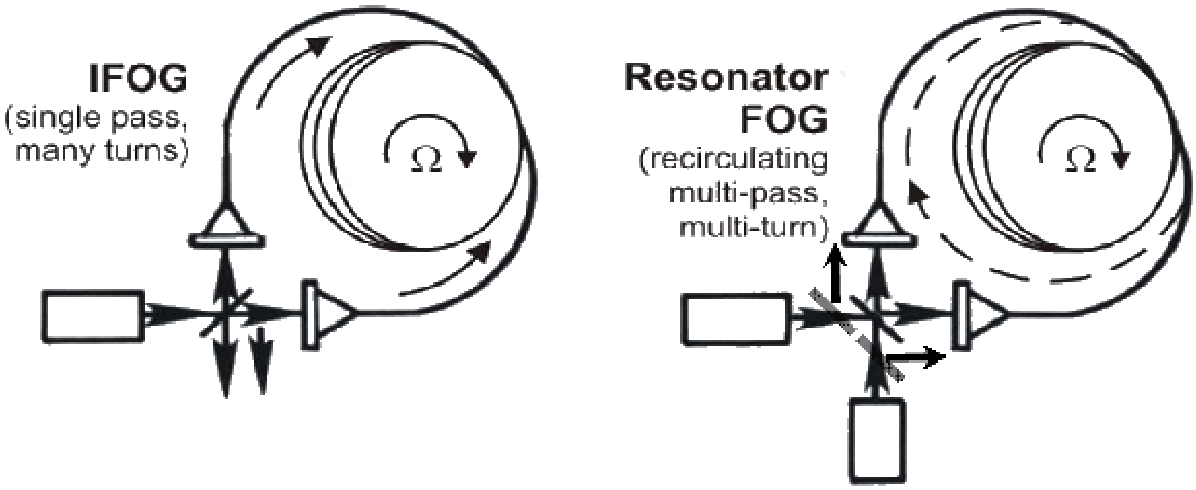

Figure 3. Interferometric FOG (left) and Resonator FOG (right). Figure from: G. A. Sanders, L. K. Strandjord, and T. Qiu, "Hollow Core Fiber Optic Ring Resonator for Rotation Sensing," in *Optical Fiber Sensors*, OSA Technical Digest (Optical Society of America, 2006), paper ME6

make up the complete gyroscope design. The following focuses on the optical fiber.

Key fiber requirements

In general, the fiber must provide a sufficient optical path length given a limited optical power budget and form factor, and it must enable high and stable performance in the presence of changing conditions. Furthermore, the choice between an IFOG or RFOG configuration set different requirements on the fiber used. These general requirements can be captured by a set of more specific performance parameters as described below.

Optical Path Length

Longer optical path lengths generally provide improved measurement sensitivity, and this can be achieved with longer fiber lengths, especially in the IFOG configuration, where lengths may extend beyond 1 km. To support that requirement, the fiber should have:

- *Low loss per unit length,* to satisfy the optical power budget allocation for fiber loss.

- *Low backscatter*, to prevent noise and associated measurement error.

- *Low nonlinearities*, such as the Kerr effect, whereby refractive index dependencies in the light-guiding material due to electric field can cause a non-reciprocal effect in the fiber loop leading to measurement error.

- *Effective coupling / interfacing*, relating to power loss and to interface reflections and crosstalk mechanisms, thereby affecting other system design decisions and overall measurement performance.

Form Factor

Smaller size is a feature of FOGs when compared to mechanical and ring laser gyroscopes. To achieve the long optical path length in a small form factor, some of the optical fiber features to consider are:

- *Small fiber glass and coating diameter*, to enable many turns of fiber in a limited coil space.

- *Low bend sensitivity*, to enable smaller coil inner diameters without compromising optical power as a result of increased bending loss.

Stability

Stable performance and low drift are especially critical in high performance gyroscopes. Fibers must provide stable performance in a number of areas:

- *Thermal stability*, such that a wide temperature range can be supported and thermal gradients do not cause non-reciprocal index changes (Shupe effect). The polarization maintaining properties of a fiber should also be insensitive to temperature.

- *Radiation insensitivity*, in particular for applications such as space and aircraft navigation/guidance.

- *Magnetic field insensitivity*, as fibers sensitive to this (Faraday effect) may require additional shielding in the gyroscope design.

Hollow core fiber

Hollow core fiber from NKT Photonics is based on microstructured fiber design using a photonic bandgap (PBG) cladding composed of silica and air holes surrounding a hollow core for guiding, as shown in Figure 4. The photonic bandgap guiding mechanism is fundamentally different from the traditional total internal reflection guiding principle in conventional fibers.

For fiber gyroscopes, hollow core fibers offer a number of advantages over solid core silica fibers. This technology provides for

- *Low nonlinearities.* As more than 98% of the mode is confined in air, not silica, the fibers are less sensitive to nonlinearities such as the Kerr effect.

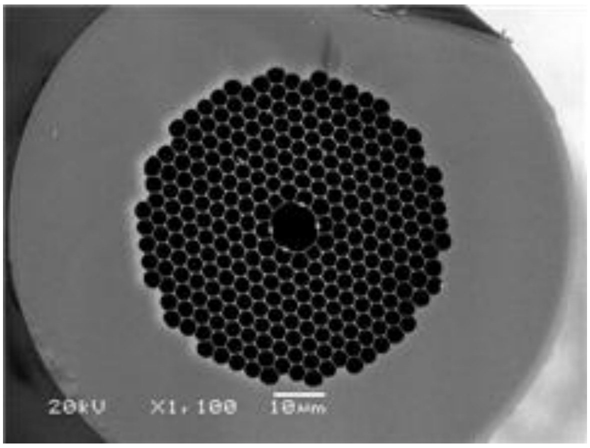

Figure 4. Hollow core fiber cross section of core and cladding region

- *Pure silica material,* with no co-dopants that can add to fiber environmental sensitivities.

- *No Fresnel reflections* at open fiber end when free-space coupling in air.

- *Polarization maintaining design* using form birefringence for low temperature sensitivity.

- *Low bend sensitivity*, fibers may be bent to very small diameters of less than 1 inch without added losses, thereby enabling smaller form factor designs.

Design examples that may be useful in FOG designs are shown in Figure 5, with both fibers designed for transmission near 1550 nm. Figure 5 (left) shows a polarization maintaining design. The core wall has an asymmetric set of glass enlargement around the core wall that are design features to create a thermally-insensitive form birefringence. Losses for this fiber are near 15 dB/km. Figure 5 (right) shows a larger core design (more multi-moded) optimized for low loss, with losses for this fiber near 3 dB/km.

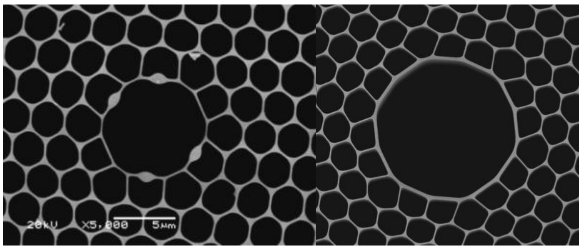

Figure 5. A polarization maintaining hollow core fiber (left), and a larger core lower loss design (right)

It is anticipated that fiber loss in a hollow core fiber will approach levels achieved by conventional fibers as the technology development continues. The opportunity for continued performance improvements with these fibers will only increase the advantages over conventional fibers. Table 1 (next page) gives a comparison of the key performance areas for hollow core and conventional silica core fibers.

Technology development Opportunities

For hollow core fibers to realize their potential and advantages over conventional fibers in fiber optic gyroscopes, continued development is needed. NKT Photonics (through its acquisition of Blaze Photonics and its Crystal Fibre subsidiary) has been the leading supplier of commercialized hollow core fibers. Through its own internal development initiatives, and in collaboration with key customers and partners, these fibers have evolved and been used in early FOG design evaluations and with positive results. Several areas for improvement that would help bring these fibers to the higher performance levels needed for practical implementation in commercial and military applications include:

Reduction of loss and backscatter

Long fiber lengths in a FOG generally offer improved measurement sensitivity. The current loss levels of hollow core fibers designed for single mode transmission limit the fiber length. Although most of the light propagates in air, the portion that interacts with the silica hollow core wall experiences scattering and other loss mechanisms due to imperfections at this boundary. Advancements in design and processing techniques will be needed to improve these properties.

Redesign for smaller fiber geometry

The hollow core fibers described herein were designed with geometries for glass and coating diameter similar to conventional telecommunication fibers. For FOG applications, coiling many turns of fiber benefits from a

Feature	Conventional fiber	Hollow core fiber	Remarks
Optical path length			
Loss (PM fiber) @ 1550 nm	< 3 dB/km	< 15 dB/km	RFOG: HC fiber should improve with continued development
Loss (PM fiber) @ 1550 nm	< 3 dB/km	< 2 dB/km	IFOG: HC fiber should improve with continued development
Nonlinearities	Kerr effect limits	Est. >100x better	Hollow core fibers have minimal Kerr effect
Coupling	Reflectivity advantage if splicing to other fiber components (IFOG)	Reflectivity advantage if free-space coupling (RFOG)	Hollow core fibers have unity index for free space coupling, so no reflections
Form factor			
Fiber diameter	Typ. 80 µm clad, 170 µm coating	Development fibers 125 µm clad, 240 µm clad	Hollow core fibers can achieve 80 µm clad, < 150 µm coating with design scaling
Fiber bend diameter	Typ. 2-3 inch	< 1 inch	PBG structure of hollow core fiber allows tight bends with no added losses
Stability			
Thermal stability	Shupe effect limits	Est. >7x better	Hollow core fibers are not as sensitive to thermally induced material index changes
Polarization maintenance - thermal stability	Poor if using stress parts for polarization maintenance	Better than stress part designs	Hollow core fibers use form birefringence for low thermal sensitivity to PM
Radiation sensitivity	Poor if using co-doped silica	Est. 50x better	Hollow core fibers have minimal radiation sensitivity
Magnetic sensitivity	Faraday effect limits (less in a PM fiber)	Est. >100x better	Hollow core fibers have minimal magnetic sensitivity; conventional fiber may require shielding

Table 1. Comparison of conventional and hollow core fibers for FOG applications

reduced diameter fiber, such as one with an 80 micron glass diameter, which is typical for many FOGs. The hollow core fibers offer improved bend sensitivity allowing for tighter coils, but require a redesign of the fiber diameter to further reduce the space occupied by the fiber on the coil. This will require design and development activity to ensure that the reduced size will not compromise the optical performance produced by the special core and cladding bandgap regions.

Develop alternative termination and coupling options

Where the FOG design can benefit from free space (air) coupling – such as in RFOG - the hollow core fiber offers a low reflectance interface, offering improved stability. Where designs require an alternative interface, such as a splice, mechanical coupling, or other type, reflections and mechanical integrity of the interface will need to be managed. Development in this area would aim to provide termination and coupling options to provide the needed packaging and performance features for any particular design.

Conclusion

Fiber optic gyroscopes are gaining in addressing many of the markets traditionally dominated by mechanical and ring laser gyroscopes, in particular those used in navigation and guidance of aircraft and spacecraft where performance requirements are demanding. Within the area of fiber optic gyroscopes, the choice of fiber type can play a key role in determining the gyroscope capabilities. Advancements in hollow core photonic bandgap fibers offer an attractive alternative to conventional silica core fibers. The “controlled free-space” guiding properties of the hollow core fibers can significantly reduce many of the performance-limiting characteristics found in conventional fibers, enabling gyroscopes with high performance, improved stability (less drift), and improved packaging. Compared to conventional fibers, the hollow core fibers are much less sensitive to radiation and temperature making the fibers suitable for FOGs for extreme environments.

Other references

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