Advantages and Disadvantages of Using New Types of Photonic Fibers in Fiber-Optic Gyros

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Abstract. In this paper, two new types of optical fibers are considered that can be used for design of a fiber optic gyroscope with improved characteristics. A fiber optic gyroscope is relatively novel type of sensors for measuring orientation and angular velocity. Characteristics of fiber optic gyroscopes significantly depend on type and quality a light source and a photonic fiber. There are also a number of effects that have a significant influence on the performance of FOG. Some of these effects can be eliminated or minimized by design. Currently, two novel types of optical fibers have been developed - microstructured fibers and multicore fibers. The use of these type of fibers can significantly reduce the effect of temperature influence on the gyroscope. In the paper the advantages and disadvantages of using of microstructured fibers and multicore fibers were discussed.

1. Introduction

The importance of optical fibers for modern science and technology is very high. Optical fiber sensing is used in medical and biological technologies, navigation systems, consumer electronics, civil and military engineering, industrial manufacture, geophysical and ecological survey, etc [1-5].

Therefore, the technologies of optical fibers are continuously improved, and new types of fibers and methods for their production are being developed [6-15].

One of the important applications of optical fibers is their use in sensors, for example, in fiber optic gyro (FOGs). FOG is an opto-electronic sensor that measures absolute angular velocity in inertial space. Its principle of operation is based on the Sagnac effect. Fig. 1 shows the working principle and principal configuration of FOG.
As shown in Fig. 1, two beams from a laser are injected into the same fiber but in opposite directions. Due to the Sagnac effect, the light traveling in counterclockwise (CCW) direction travels faster than the light in clockwise (CW) direction when a fiber loop is rotated in CW direction at the rate of $\Omega$. So, if we know the resulting differential phase shift, we can calculate $\Omega$ by using the following formula [16]:

$$\Delta \phi = \frac{2\pi LD}{\lambda c} \Omega,$$

where $\lambda$ is the wavelength of light beam, $c$ is the speed of light, $L$ is the length of the fiber; $D$ is the diameter of the fiber loop.

It is obvious that the accuracy and other operational characteristics of FOG are largely dependent on the optical properties of the fiber and the laser source. The major reason of the FOGs error is nonreciprocity of sensing coil due to Rayleigh backscattering, Shupe, Kerr, Faraday effects, etc.

The influence of some of these effects can be eliminated with the help of design solutions. For example, the Rayleigh backscattering effect do not lead to the appearance of nonreciprocity if a semiconductor wideband superluminescent diode is used as light source [16].

On the other hand, the influence of a number of factors cannot be easily reduced or avoided. Such factors include, for example, thermal effects on the sensor. The thermal influence is the largest error source in FOGs. The thermal influence can lead to Shupe effect, thermal deformation of the coil case and the fiber, problems with electronics components of FOG.

In the paper the advantages of using new types of optic fibers in FOG in terms of reducing the effect of thermal effects on FOG’s characteristics will be discussed.

2. Novel Types of Optic Fiber for FOGs

The one of the most unwanted results of thermal influence is the Shupe effect. The Shupe effect results when time-varying spatial gradients arising from, for example, thermal influence on the fiber optic sensing coil occur. At present, a number of approaches have been developed to minimize the effect of thermal gradients on FOG characteristics [17]. Some of them suppose the use of new types of optical fibers, for example, microstructed fibers with solid or air core [18-20] (Fig. 2), multi-core fibers [21] (Fig. 3).
Figure 2. Microstructured fibers: (a) silica hollow-core photonic bandgap fiber; (b) silica hollow-core kagome lattice fiber which guides by the inhibited coupling mechanism; (c) silica hi-NA fiber, (c) IEEE; (d) silica birefringent fiber; (e) single-mode microstructured polymer optical fibers; (f) high bandwidth microstructured polymer optical fibers.

Figure 3. Micrographs of two strongly-coupled multi-core fibers used to devise sensors.

3. Advantages and Disadvantages of Using New Types of Photonic Fibers
Advantages of microstructured fibers (MSF) are:
- the thermoelastic deformation of MSFs can be substantially lower than deformation of the conventional fibers in conditions of the same thermal influence [20];
- the thermal gradients in MSFs is less than in the conventional fibers;
- the temperature equalization velocity is higher in MSFs compared to the conventional fiber.

The value of these differences depends on a lot of factors such as the diameter of the microstructured fiber, the amount of air rods and their arrangement, etc.

Another very important advantage of microstructured fibers is that the air rods can be filled with various materials, for example, a certain gas mixture or a certain type of nanomaterial. That will allow to obtain fiber with unique optical and thermal properties.

For example, the using of microstructured optical fiber with air rods filled with thermally conductive nanoparticles, e.g. carbon nanotubes, can significantly reduce the temperature gradients (up to 10 and more times) in the optical fiber coil in comparison with FOGs based on conventional optical fibers [22].
The using multi-core fibers (MCF) in FOGs has two clear advantages. At first, using multi-core fibers allows to drastically reduce the fiber length and make fiber coil very compact while maintaining the gyro’s sensitivity [23]. These become possible due to the small core-pitch of MCF and to the number of turns decreases by a factor of the number of cores in the fiber.

At second, the flexibility and comprehensiveness of core-to-core connectivity at the end of MCF having any core arrangement. This advantage is particularly effective for MCFs with large number of cores and/or complex core-arrangement [23]. Along with the above benefits, all known methods can be used to reduce the influence of undesirable effects like Shupe effect - thermal stabilization systems, specific winding patterns, etc.

The main disadvantage of using the MSF and MCF is the need for changes in the FOG design. So, the functional diagram of the open-loop FOG with MCF is shown in Fig. 4 [23].

![Functional diagram of the open-loop FOG with MCF](image)

As can be seen from Fig.2 and Fig.4, the functional diagram of the of the FOG with MCF is more complicated than of conventional FOG. Thus, for the use of FOG with MCF instead of conventional FOG in harmful operating conditions like space, additional research is needed.

Also, microstructured fibers have two problems. The first problem is the process of manufacturing of microstructured fibers is rather expensive and complex. The second one is the significant loss rate (about 50 dB/km), but it was theoretically shown the possibility of reducing loss rate to 0.0005 dB/km. Currently research is underway to solve these problems and to improve the properties of microstructured fibers.

4. Summary
Both novel types of photonic fiber look promising for use in FOGs. Progress in nanotechnology allow to create microstructured fibers with unique optical and thermal characteristics. And the using such microstructured fiber in FOGs can decrease the Shupe effect impact on operational FOG characteristics due to significant reduction of the temperature gradients in the optical fiber coil.

The use multi-core fibers allow to make the FOG more compact and fabrication process of FOGs cheaper due to significant reduction in fiber length. So, as shown in [23], the angular random walk performance of 0.002 deg/√h can be achieved for open-loop FOG with 700 m seven-core fiber.

But the use of these types of photonic fibers lead to more complicated FOG design. And additional research is needed before these fibers will be used for FOGs which have to operate in harmful conditions like vacuum, magnetic influence, cosmic ray and sun radiation, etc.

5. References
[1] Zhang Y, Su H, Ma K, Zhu F, Guo Y, Jiang W 2018 Optic-Fiber Temperature Sensor in: Ivanka Stanimirovic and Zdravko Stanimirovic (Eds.) Temperature Sensing, IntechOpen doi: 10.5772/intechopen.74207
[2] Talataisong W, Ismaeel R, Lee T, Brambilla G 2019 Optical fibers for bio-sensing applications J. Phys.: Conf. Ser. 1151 012003
[3] Shao L, Liu Z, Hu J, Gunawardena D, Tam H-Y 2018 Optofluidics in Microstructured Optical Fibres Micromachines 9(4) 145 doi:10.3390/mi9040145
[4] Bhowmik K, Peng G-D 2019 Polymer Optical Fibers in: Handbook of Optical Fibers Springer Nature, Singapore Pte Ltd.
[5] Amezcua-Correa R, Antonio-Lopez E, Arrizabalaga O, Zubia J, Schülzgen A and Villatoro J 2018 Multicore Optical Fiber Sensors CLEO Pacific Rim Conference 2018 OSA Technical Digest (Optical Society of America, 2018) paper W4L.2
[6] Goodarzi A, Ghaanaatshoa M, Mozafari M 2018 All-optical fiber optic coherent amplifier Scientific Reports 8(1) 15340
[7] Perrone P, Bettì S, Rutigliano G G 2018 Multidimensional Modulation in Optical Fibers Res J Opt Photonics 2(1)
[8] Optical fiber connector and optical fiber assembling method 2015 U.S. Patent US 8944699 B2
[9] Single-mode optical fibers for optical fiber connectors 2013 U.S. Patent US 8764311 B3
[10] Manufacturing method for optical fiber preform and optical fiber 2010 U.S. Patent US 869383B2
[11] Universal optical fibers for optical fiber connectors 2015 U.S. Patent US 904692B2
[12] Macho A, Llorenté R, García-Meca C 2018 Supersymmetric Transformations in Optical Fibers Phys. Rev. Applied 9 014024
[13] Radial emissions from optical fibers 2018 U.S. Patent US10092356B2
[14] Özlem Unverdi N, Aydın Unverdi N, Canbay C 2005 The Variation of The Modal Propagation Constant with Temperature in Coupled Bent Optical Fibers 4th International conference on electrical and electronics engineering (Bursa, Turkey) Information on http://www.emo.org.tr/ekler/7e51e9d1cf800f_ek.pdf
[15] Yin S, Kim J H, Ruffin P B, Luo C 2006 An investigation on fiber optic gyroscopes using microstructured fibers Proc. SPIE 6314, Photorefractive Fiber and Crystal Devices: Materials, Optical Properties, and Applications XII, 63141H doi: 10.1117/12.680089
[16] Andronova I A, Malykin G B 2002 Physical problems of Sagnac-effect fiber gyroscope Phys. Usp. 45(8) 793–817
[17] Meshkovsky I K, Miroshnichenko G P, Rupasov A V, Strigalev V E, Sharkov I A 2014 Investigation of the influence of thermal effects on the operation of fiber-optic angular rate sensor XXI International conference on integrated navigation systems 191–202
[18] Terrel M A, Digonnet M J F 2012 Fan Resonant Fiber Optic Gyroscope Using an Air-Core Fiber Journal of Lightwave Technology 30(7) 931–937
[19] Argyros A 2009 Structure, properties and characteristics of optical fibres in: Handbook of Textile Fibre Structure: Natural, Regenerated, Inorganic and Specialist Fibres
[20] Barulina M A, Pankratov V M, Efremov M V 2016 The temperature effect on fiber optic gyroscopes based on air-core photonic crystal fiber, 23rd Saint Petersburg International Conference on Integrated Navigation Systems ICINS 2016 – Proceedings 23 93-97
[21] Villatoro J, Arrizabalaga O, Antonio-Lopez E, Zubia J, I S de Ocáriz 2017 Multicore Fiber Sensors in: Optical Fiber Communication Conference, Osa Technical Digest (Online) Optical Society of America: (Washington, DC, USA)
[22] Golikov A V, Pankratov V M, Pankratoava E V 2016 Thermal Processes in the Bay of the Fiber Optic Gyroscope Based on the Micro-Structured Optical Fibers with Carbon Nanotubes Nano-and microsystems technology 18(10) 604-613
[23] Mitani S, Nigo K, Karasawa S, Tottori Y, Ehdo H, Takahata T 2018 Interferometric Fiber-Optic Gyroscope Using Multi-Core Fiber 2018 European Conference on Optical Communication (ECOC) (Rome) 1-3
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