Interferometric Fiber-Optic Gyroscope Using Multi-Core Fiber

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***Abstract*— We proposed a novel interferometric fiber optic gyro (I-FOG) sensor coil consisting of multi-core fiber (MCF) spliced with fan-in/fan-out (FIFO) devices. We fabricated a 102-m long, seven-core MCF coil with FIFO devices and demonstrated the operation of the proposed I-FOG for the first time to our knowledge. The angular random walk performance of 0.002 deg/√h was achieved, thereby confirming that the seven-core waveguide loop works successfully as a Sagnac interferometer as expected.**

***Index Terms*— Interferometric fiber-optic gyroscope, Sagnac effect, Space division multiplexing, Multi-core fiber, Fan-in/fan-out, Free space optics**

I. Introduction

IMPROVING the sensitivity of the interferometric fiber-optic gyroscope (I-FOG) as a rotation-rate sensor contributes to usher in a new era of highly precise and autonomous mobile systems in space, marine and other applications. One solution for such sensitivity improvement is applying long fiber in the sensing coil. In fact, it is reported that the 5-km-long polarization-maintaining fiber coil have been used for space navigation grade [1] and a giant I-FOG with a 15-km-long single mode fiber coil is demonstrated for low noise property [2].

However, longer sensing fiber loop causes other problems. A non-reciprocal phase shift error [3] becomes relatively high compared to the reduced short-term noise and the unique manufacturing process of winding called symmetry winding [4] is inevitable. Symmetry winding process must require perfect qualification without coil turn number error or winding flaw. Therefore, the unique manufacturing process of winding such a long length of fiber into multiple layers to form a coil requires elaborate and costly skill.

To solve for the above problems in I-FOGs, here, we discuss a new approach by using multi-core fibers (MCFs). So far, MCF technologies including their related optical devices have been massively exploited to increase the transmission capacity in optical networks [5]-[8]. Recently, MCFs having a few tens of transmission cores have been developed, and their feasibility was successfully examined in Peta-bit/s–scale transmission experiments [7][8]. In Ref. [9], the possibility of using MCFs in I-FOGs has been briefly discussed, but, the practical implementation of the MCF coil has not been shown yet.

In this paper, we propose a novel configuration of a fiber coil using an MCF and a pair of fan-in/fan-out (FIFO) devices, and show that an integrated single optical path can be formed by connecting multiple cores' optical paths in serial. Thus, the effective fiber length can be increased by a factor of the number of cores, which leads to higher sensitivity. We first explain the proposed configuration of the fiber coil and discuss its advantages. Then, we fabricate the proposed fiber coil by using a 102-m long, seven-core MCF and implemented it into an open-loop I-FOG system. (Hereafter, we call it 'MC-FOG.') In the experiment, we confirm its superior performance as a rotation sensor.

II. Operating Principle And Problems Of I-FOG

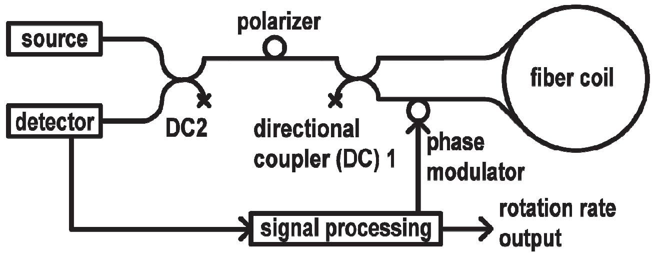

Fig. 1. Schematic of conventional I-FOG configuration.

In order to clarify the advantage of using MCF, we first briefly explain the operation of a conventional I-FOG. Figure 1 shows a schematic of the I-FOG. The signal light (from a broadband light source) is divided by directional coupler 1 (DC1), and the two divided beams propagate in the fiber coil in the clockwise (CW) and counterclockwise (CCW) directions. Then both beams are recombined by DC1. As is well known as the Sagnac effect, a relativistic phase delay occurs depending on the rotation rate, and the phase difference between both beams (in the CW and CCW directions), $\Delta\phi_R$, can be expressed as:

$$\Delta\phi_R = (2\pi LD/\lambda c)\cdot\Omega \quad (1)$$

where Ω is the rotation rate, L is the length of fiber in the coil, D is the diameter of the fiber coil, and λ and c are the wavelength

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and speed of light in vacuum [10], respectively. Thus, the phase shift is proportional to Ω and can be measured by detecting the interference signal.

In Eq. (1), the scale factor $2\pi LD/\lambda c$ expresses sensitivity relative to the rotation rate, and the design guideline for better sensitivity is to increase L. However, increasing L is not so simple due to a problem intrinsic to the I-FOG, called the Shupe effect [10]. It entails a non-reciprocal phase shift caused by a time-varying distribution of temperature and stress in the fiber coil, and inevitably leads to measurement error depending on the environmental conditions [3]. In order to mitigate the influence of this effect, a unique winding pattern (called symmetrical winding) is typically applied to the coil [4]. This entails, however, a very meticulous winding process, and the number of turns of the fiber coil consequently increases the manufacturing cost. In addition, because an imperfect winding pattern could actually enhance measurement error, it is not easy to make a coil with a long length of fiber.

III. Proposed Fiber Coil Using MCF And FIFOs

In order to mitigate the above problems in conventional I-FOGs, we propose a novel fiber coil configuration. Figure 2 shows a schematic of the proposed fiber coil using an N-core MCF and a pair of FIFO devices. (In the case of MCF, spatial multiplexers/demultiplexers are referred to as fan-in/fan-out (FIFO) devices and are used to efficiently couple light from individual single mode fibers to each core of the MCF and vice versa.)

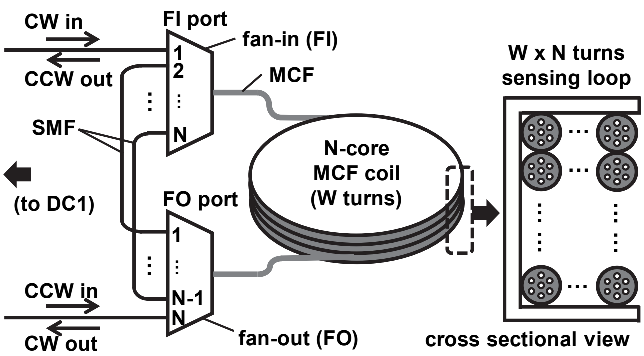

Fig. 2. Schematic of the proposed fiber coil using MCF with bundled N-core waveguides.

Here, port n of the FI device is connected to the port (n-1) of the FO device ($n = 2,\cdots,N$). Port 1 of the FI device and port N of the FO device are connected to DC1, and thus serve the role of input/output for the fiber coil. For example, the signal source light is led into port 1 of the FI device, travels in the CW direction through all the MCF core's waveguides N times, and is derived from port N of the FO device. In this way, an integrated single waveguide loop is realized by using FIFO devices, and the fiber coil's effective optical path length can be increased by a factor of N.

One of the clear advantages of using MCF is that it allows us to drastically reduce the fiber length while maintaining the gyro's sensitivity. Since the number of turns of the fiber coil becomes $1/N$, the cost of the winding process can be also drastically reduced. Moreover, due to the small core-pitch of MCF, many core waveguides are densely packed in the coil. This results in the fiber coil being very compact, thereby the influence of the Shupe effect could be suppressed to some extent.

Another advantage of using MCF with FIFO devices is 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.

On the other hand, MCF and FIFO devices essentially introduces wavelength-dependent crosstalk between different cores, that could act as noise or interferences in the proposed system. The impact of the crosstalk among core channels is a unique problem on the proposed I-FOG using MCFs and is still an open question to be discussed in the future study.

IV. FIFO Devices For MCF Gyroscope

Various configurations of FIFO have been reported so far. The most common techniques use: 1) fused tapers or bundled fibers [11][12], 2) 3D waveguides [13][14] and 3) free space optics [15][16]. Table I shows the advantages and disadvantages of each type of configurations. The key parameters which could affect the sensing performance and the practical implementation are the insertion loss, crosstalk among core channels, compactness, and so on. Therefore, the proper choice of the FIFO devices is important. Even though each of these approaches has its own merits, it is still challenging to realize low crosstalk for highly-dense MCFs having a small core pitch distance.

Connection using fused tapers and that using 3D waveguides are associated with comparatively large splice loss and waveguide loss, although they are effective to realize a small-sized coil. On the contrary, connection using free space

TABLE I
Various Configurations Of FIFOs

Configuration	Advantage	Disadvantage
Fused tapers	Small size	Large fused loss
3D waveguides	Small size	Large waveguide loss
Free space optics	Low loss Low crosstalk	Large size

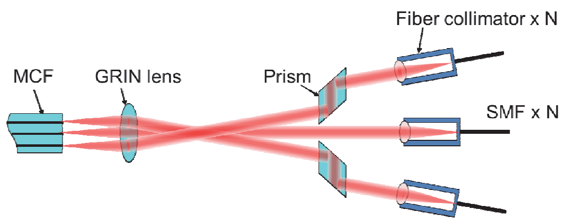

Fig. 3. Schematic diagram of the inside of FIFO devices using free space optics for N-core MCF

optics enables sufficiently low loss connectivity with sacrificing the size of the coil. Free space optics configuration has additional advantages of low crosstalk and low polarization-dependent loss (PDL). Figure 3 shows a schematic diagram of the inside of the free-space-optics type of FIFO device. The signal lights transmitted through the cores of the MCF are collimated with a GRIN lens and separately launched into the corresponding fiber collimators. In this way, the optical connection between MCF and *N* SMFs can be realized and this device can work as a fan-in device (from *N* SMFs to MCF) as well as a fan-out device (from MCF to *N* SMFs). Since the signal lights are separated in space, the crosstalk is essentially small. In addition, unlike waveguide devices, the polarization dependence is also small. These properties are suitable for application in the I-FOG. As the result of the above trade-off, we adopted the free space optics for the experimental hardware which is explained in the next section.

As for FIFO design, we utilized a seven-core MCF which has hexagonal close–packed structural core arrangement design. Table II shows its specifications. The cladding diameter of MCF is 150 µm. The mode field diameter of its cores is 10 µm. The cores are being placed with the pitch of 45 µm. The measurement results of fabricated FIFO devices are shown in Table III. Although their size reduction remains to be implemented, low loss and PDL properties were successfully achieved in both of Fan-In and Fan-Out.

TABLE II
SPECIFICATIONS OF THE UTILIZED MULTI-CORE FIBER [17]

Item	Specification	Description
Number of cores	7	Core arrangement design; Hexagonal close–packed structure
Core pitch	45±1 µm	
Clad diameter	150±1 µm	
MFD	10±1 µm	At 1550 nm
Crosstalk	≤ −30 dB/km	At 1550 nm
Cutoff wavelength	≤ 1530 nm	

TABLE III
PERFORMANCE OF THE FABRICATED FIFO (FREE SPACE OPTICS)

Item	Measurement	Description
Size	ϕ28 x 88 mm	Without pigtails
Insertion loss	< 0.3 dB	All 7 ports
PDL	< 0.05 dB	All 7 ports
Return loss	> 50 dB	All 7 ports

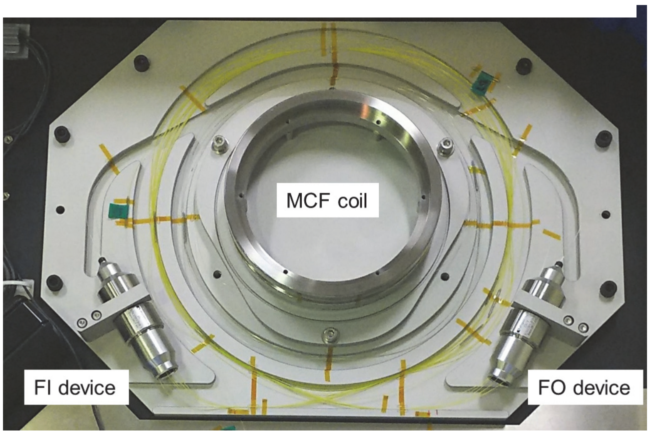

Fig. 4. Fabricated fiber coil using seven-core MCF and FIFO for demonstration purposes.

V. EXPERIMENTAL SETUP OF A SEVEN-CORE MC-FOG

For demonstration purposes, we fabricated the proposed MCF coil implemented in an I-FOG system. Figure 4 shows a photograph of the fabricated coil. A 102.7-m long MCF was wound on a titanium bobbin (ϕ128 mm) with the symmetric winding pattern (octupole winding) with a total of eight layers. The loss of the wound MCF at the center core was measured to be 0.39 dB/km at a wavelength of 1550 nm.

We also used the pair of FIFO devices based on free-space optics shown in previous section. The FIFO devices and the MCF coil were fusion-spliced. Table IV summarizes the fabricated MCF coil performance. The total optical path length of the sensing loop was 823.8 m, including the extra length of MCF and the length of the seven SMFs between the FI and FO. The total insertion loss and PDL of the fiber coil (including the FIFOs) were measured to be 8.4 dB and 0.05 dB, respectively. It should be noted that the total insertion loss is increased by the splicing losses among the MCF coil and the FIFO devices.

TABLE IV
PERFORMANCE OF THE FIBER COIL COMPOSED OF MCF AND FIFO

Item	Measurement	Description
Total optical length	823.8 m	
Insertion loss	8.40 dB	
PDL	0.05 dB	
Return loss	45.9 dB	for the light launched from “CW in” in Fig. 2
	48.0 dB	for the light launched from “CCW in” in Fig. 2

We then constructed an MC-FOG by using the seven-core fiber coil, as shown in Fig. 5. In order to focus on the fiber coil’s performance, we implemented an open-loop system in which a simple lock-in detection is used to obtain the rotation rate, (rather than a digital closed-loop system in which the detected signal is feedbacked for wider measurement range with good linearity, thereby concealing the coil’s imperfection [10].) As a broadband light source, we used a super-luminescent diode (SLD) with output power of 25 mW and a spectral width of 50 nm. The SLD output was led to an integrated optical circuit (IOC) consisting of a Y-branch waveguide and a push-pull phase modulator (for lock-in detection of the phase shift), divided into CW and CCW light

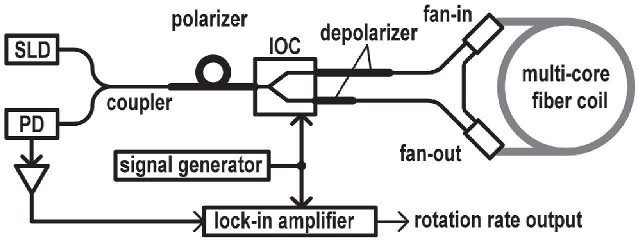

Fig. 5. Functional diagram of the implemented MC-FOG open-loop system.

signals, and phase-modulated with a rectangular signal at frequency f_m. We set f_m to 127.6 kHz, which corresponds to the inverse of the propagation time of the fiber coil's optical path length.

The signals were then depolarized by passing through the Lyot fiber depolarizer which need to be inserted because the MCF is non-polarization-maintaining type [10], and led into the fiber coil shown in Fig. 4. The output signals from the fiber coil were recombined at the IOC, and their interference signal was detected by a photodetector (PD). In this experiment, the power received at the PD was measured to be 20.4 µW, which was sufficient for I-FOG operation. By using the lock-in amplifier, we demodulated the amplitude at f_m and derived phase shift $\Delta\phi_R$ (i.e., the rotation rate).

VI. Performance Of The Seven-Core MC-FOG

First, we set the fiber coil on the rotation table as is shown in Fig. 6 and measured sensitivity relative to the rotation rate. Figure 7 shows the measurement result of the rotation rate in the range of ±10 deg/s (applied around the rate-sensitive axis). As can be seen, the proposed system could sense the rotation rate even at a higher rate of rotation.

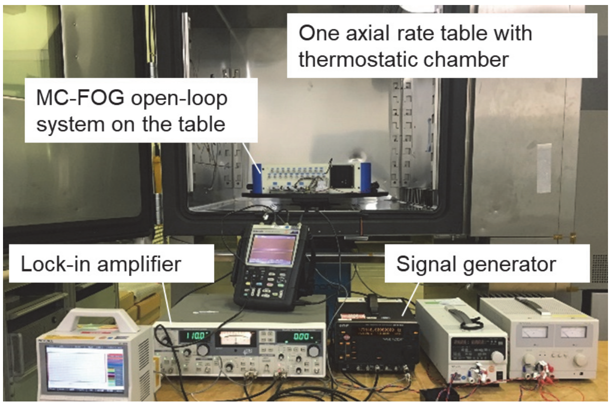

Fig. 6. MC-FOG placed on the rotation table and measurement instruments.

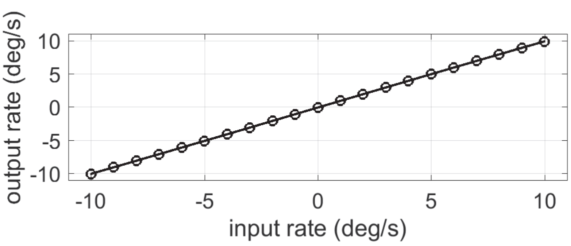

Fig. 7. Measured rotation rate in the range of 10 deg/s.

Next, in order to evaluate the measurement limit of using this MCF coil, we placed the fiber coil horizontally so that its sensitive axis would be vertical, and recorded the measured rotation rate derived by the proposed system at rest. Figure 8 shows the measurement result for 12 hours at a sample rate of 1

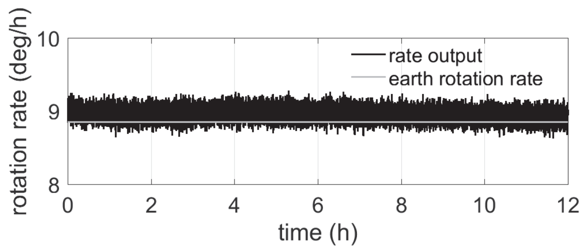

Fig. 8. Output rate profile at 1 Hz sampling statically.

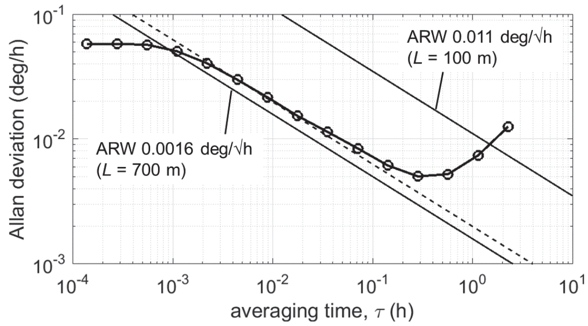

Fig. 9. Allan deviation plot and theoretical ARW noise limit.

Hz. It should be noted that Earth's rotation rate was 8.85 deg/h around the vertical axis at our experiment site (latitude: 36.022°). As can be clearly seen, this system has sufficient performance to sense Earth's rotation rate.

Figure 9 shows the Allan deviation derived from the result in Fig. 8. From the part with a $1/\sqrt{\tau}$ slope, we can calculate the angular random walk (ARW). (Note that ARW expresses the power of rate noise in the short term.) From Fig. 9, ARW of this system was measured to be 0.002 deg/√h. We also calculated the theoretical limitation of ARW caused by the shot noise of the signal received at the detector and the excess relative intensity noise (RIN) of the light source [10]. The two solid lines and the dotted line in Fig. 9 show the theoretical ARWs for I-FOGs with 100-m and 700-m long fiber coils, and measured ARW, respectively. Although only the 102-m long fiber was used, its performance was very close to the theoretical limit of that of the 700-m long fiber coil. In this way, the advantage of using MCF was clearly confirmed.

Before concluding this section, we briefly discuss the Shupe sensitivity of the fabricated MC-FOG. Here, we conducted a simple experiment to evaluate the temperature changing rate dependence (i.e. Shupe effect) of the rotation rate bias measured by the fabricated MC-FOG [18]. In this experiment, we covered the MCF coil and FIFO devices with an aluminum chassis, and attached ceramic heaters onto the chassis directly to control the temperature of the sensing elements. We gradually changed the temperature of the chassis while measuring the rotation rate. The starting temperature was 25 °C (room temperature), and the chassis was heated with a changing rate of about 0~200 °C/h. Once the temperature was raised to 36 °C, the heater was turned off and the chassis was cooled down to room temperature again. During this temperature change, the sensitive axis of the MCF coil was kept vertical statically. Then, by using the measured rotation rate, we expressed the rotation rate bias as a function of the temperature and the temperature changing rate, and numerically separated their contributions (to evaluate the Shupe sensitivity). The results of Fig. 10 showed that the excellent low sensitivity to the temperature changing rate was measured to be less than 0.001 deg/h/(°C/h). For further discussion, experimental and analytical studies on MC-FOGs with various types of winding pattern would be pursued, although we successfully demonstrated that the fabricated MC-FOG had a low Shupe sensitivity for application in strategic grade (< 0.001 deg/h [10]) gyroscope sensors.

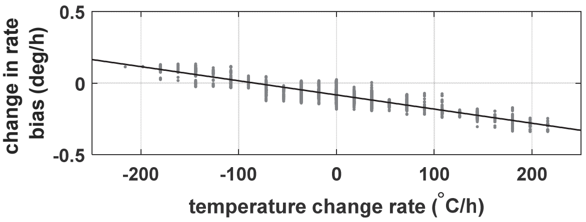

Fig. 10. Temperature changing rate dependence of measured rotation rate bias (Shupe sensitivity) of the fabricated MC-FOG. The gray dot plots show the change in the rotation rate bias as a function of the temperature changing rate (obtained from the measured rotation rate bias data), and the solid line shows its linear fitting. Its linear coefficient is less than 0.001 deg/h/(°C/h).

VII. Conclusion

A novel configuration of an optical gyroscope which consists of multi-core fiber (MCF) and fan-in/fan-out (FIFO) devices was proposed, and demonstrated for the first time to our knowledge. The demonstration of the MC-FOG will expand the possibility of MCF's new application and further development of I-FOG sensor. Since it is reported that the number of MCF cores increases to 36 cores currently [7][8], extremely longer optical loop coil more than 10 km, for example, can be implemented with a shorter physical fiber length. Trial production and performance evaluation of this kind of optically longer coil are awaited. In practical use, temperature dependence of the MCF coil including the FIFO is of great importance. Although we briefly mentioned Shupe sensitivity in this paper, the detailed analysis will be reported in future papers.

For future prospects, it is necessary to consider the miniaturization of MCF coil including FIFO and the practical product integration. Due to the size of FIFO that we utilized, the MC-FOG fabricated is large, but it is reported that the same free-optics type of FIFO is downsized to 28 mm in length [19].

Finally, in order to improve the low-drift performance to be operated as I-FOG, the following two items are worth to be considered: (1) the integration of MC-FOG into digital closed-loop, (2) development polarization-maintaining (PM) MCF and PM FIFO and applying them to the MCF coil.

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