An overview of Optical Gyroscopes Theory, Practical Aspects, Applications and Future Trends

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Contents

Introduction

Since the discovery of the Sagnac effect, in the beginning of the 20th century, an interest has increased in the making of optical rotation sensors. The first chapter of this report will describe the the Sagnac effect which forms the theoretical basis for optical gyroscopes. According to the Sagnac effect, two light waves, propagating in opposite directions through the same closed optical path, show a traveling time difference proportional to the rotation rate of the optical path, relative to the inertial frame. As will be further on showed, this effect is dramatically small and advanced technologies and methodologies had to be developed in order to enable sensitive rotation measurements using the Sagnac effect. The first ring laser gyroscope (RLG) was built in the 1960's, with the evolution of lasers, and is now considered a mature and extremely accurate technology . The second chapter of this report will discuss this type of gyroscope in detail. With the introduction of fiber optics, it became possible to design smaller, lower cost products. The interferometric fiber optic gyroscope (I-FOG) was developed in the late seventies and is now considered the most popular type of optical gyroscope, used in a vast variety of applications. The third chapter will describe the I-FOG principles, and discuss the major technical difficulties which limit its sensitivity. Due to the practical significance of this type of gyro, I have chosen to expand this chapter in more details. The advantages of optical gyroscopes over traditional spinning mass gyros are significant - not only that they are gradually replacing the old types in different applications, but they also open up opportunities for new types of applications. The forth chapter of this report will briefly present various actual applications of optical gyros, and their requirements from a rotation sensor. Finally, in the 5th chapter, two types of new optical gyros will be presented: first we will discuss the resonant fiber optic gyro (R-FOG), which is now in final research stages and may significantly improve the sensitivity of current I-FOG's. Second, we will present the revolutionary approach of using photonic crystals as a medium for compact optical gyros, which is now in early stages of research.

Chapter 1

The Sagnac Effect

1.1 Background

As mentioned in the introduction to this thesis, all optical gyroscopes are based on the principles of the Sagnac effect. The phase accumulated by a light wave, which propagates along a slowly rotating circular path, depends linearly on the rotation rate of the path. As a result of that, two counter-rotating waves traveling through the same circular path, will exhibit a phase difference. The first experiments concerning light propagating in rotating media, were in fact carried out F. Harrenss in 1911. Harrness, however, failed to interpret his results properly and hence George Sagnac was credited for the effect when he published his results in 1913.

In order to get a good understanding of the Sagnac effect, we shall first consider a perfect circular path. A light entering the path, is split by a beam-splitter into two beams: one propagating clockwise, and one propagating counterclockwise. If the system is at rest, both light beams travel through the same optical path and return in phase to their origin. Now, let us assume that the entire system is rotating clockwise in an angular velocity $\mathbf{\Omega}$ relative to the inertial system. In that case, a difference in the optical path between the two beams will occur. This is illustrated in figure 1.1: since the origin of the waves rotates with the system (clockwise) an observer, moving along with it, will notice that the beam which is rotating clockwise (the co-rotating beam) had to go through a longer distance than the beam rotating counterclockwise (the counter-rotating beam), in order to return to the origin. The phase difference $\Delta\phi$ can now be measured using an interferometer.

1.2 Calculation of the Phase Shift

We shall now calculate the phase difference for the case which was described above: Let t_+ and t_- be the traveling times of the co-rotating and counter-rotating beams accordingly. Let R be the radius of the circular path and c the velocity of light in vacuum. The optical paths can now be calculated for both beams:

$$ct_+ = 2\pi R + \Omega R t_+ \quad \Rightarrow \quad t_+ = \frac{2\pi R}{c - \Omega R} \tag{1.1}$$
$$ct_- = 2\pi R - \Omega R t_- \quad \Rightarrow \quad t_- = \frac{2\pi R}{c + \Omega R}$$

The difference in optical paths is given by:

$$\Delta L = ct_+ - ct_- = 2\pi R \left(\frac{1}{1 - \frac{\Omega R}{c}} - \frac{1}{1 + \frac{\Omega R}{c}} \right) \approx \frac{4\pi \Omega R^2}{c} \tag{1.2}$$

Where we have used the first order approximation in $\frac{\Omega R}{c}$. It is important to note, that this approximation is more than enough for any practical case involving an optical gyroscope, where the velocity (ΩR) is much smaller than the speed of light. Since in first order in $\frac{v}{C}$ causality is conserved, this result is correct for an observer in the inertial system as well as for one in the rotating system. The phase difference between the two beams can now be calculated from equation (1.2):

$$\Delta\phi = \frac{2\pi \Delta L}{\lambda} = \frac{8\pi \Omega A}{c\lambda} \tag{1.3}$$

Where A is the area of the circular path and λ is the wavelength. We can see from equation (1.3) that the Sagnac phase difference is proportional to the area and to the angular velocity of the rotation. This fact shows that the larger the area of the system, the more sensitive the effect is to smaller angular velocities. As we shall further on see, this conclusion is important for the making of the fiber optic gyroscope. Although the above arguments discussed the specific case of an ideal circular path, the Sagnac phase difference can be generalized and extended into any rotation axis and any closed path. If we define an equivalent area vector of the closed path to be:

$$\boldsymbol{A} = \frac{1}{2} \oint \boldsymbol{r} \times \boldsymbol{dr} \tag{1.4}$$

We can write the Sagnac phase difference as:

$$\Delta\phi = \frac{4\omega}{c^2} \boldsymbol{A} \cdot \boldsymbol{\Omega} \tag{1.5}$$

Where $\boldsymbol{\Omega}$ is the rotating vector. This generally describes the Sagnac effect as the rotation vector flux which goes through the enclosed area.

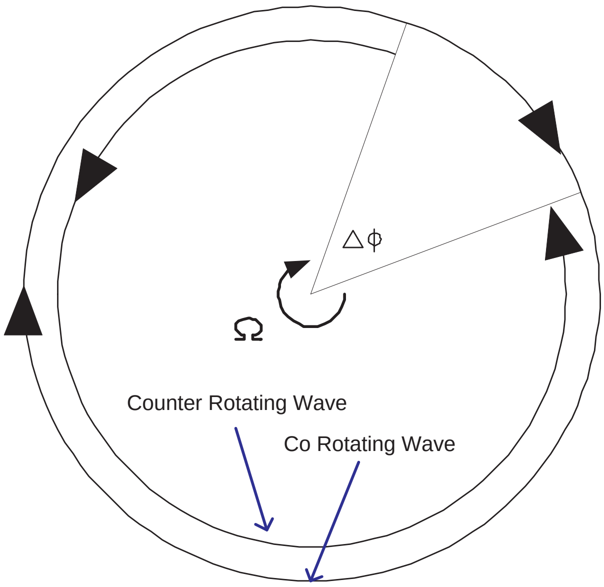

Figure 1.1: Phase shift between two counter-propagating waves

1.3 The Material Effect

In fiber optics, light propagates through a certain material. Therefore, it is necessary to ask the if the previous result for the Sagnac effect changes due to the effect of the material. We shall consider the same configuration of figure 1.1, and assume that the light propagates inside a material with refractive index n. The velocity of light in the media can be added in a relativistic manner to the tangential velocity of the medium, to obtain c_+ and c_- as the velocities of light propagation in the medium clockwise and counterclockwise respectively. We can take the first order terms in $\frac{v}{c}$, of the relativistic addition, and hence equation (1.1) becomes:

$$c_+t_+ = \left(\frac{c}{n} + \Omega R\left(1 - \frac{1}{n^2}\right)\right)t_+ = 2\pi R + \Omega R t_+ \quad \Rightarrow \quad t_+ = \frac{2\pi R}{\frac{c}{n} - \frac{\Omega R}{n^2}} \tag{1.6}$$

$$c_-t_- = \left(\frac{c}{n} - \Omega R\left(1 - \frac{1}{n^2}\right)\right)t_+ = 2\pi R - \Omega R t_- \quad \Rightarrow \quad t_- = \frac{2\pi R}{\frac{c}{n} + \frac{\Omega R}{n^2}}$$

The difference in optical paths previously given by equation (1.2) can now be written as:

$$\Delta L = c(t_+ - t_-) = 2\pi R n\left(\frac{1}{1 - \frac{\Omega R}{nc}} - \frac{1}{1 + \frac{\Omega R}{nc}}\right) \approx \frac{4\pi\Omega R^2}{c} \tag{1.7}$$

Where first order at $\frac{\Omega R}{nc}$ was taken. We see that the optical path difference is identical to that in vacuum. The phase difference therefore, also remains unchanged.

1.4 Some Typical Numbers

The Sagnac effect is very small. In order to get a good feeling of the effect's magnitude, let us consider a simple example. Let us take, for instance, the earth rotation velocity:

$$\Omega_E = 15 \frac{deg}{hour} = 7.3 \times 10^{-5} \frac{rad}{sec}$$

Now assume we have a ring of radius $R = 5cm$, and a laser of wavelength $\lambda = 633nm$ is used as a light source for the system. The phase difference will be given by:

$$\Delta\phi = \frac{8\pi^2 R^2 \Omega_E}{c\lambda} = 7.6 \times 10^{-8} rad \quad (1.8)$$

This is truely a small number. As we shall further on see, many applications of gyroscopes require sensitivity of up to $10^{-3}\Omega_E$, and therefore sophisticated methods need to be developed in order to be able to measure such small phase differences. The most obvious approach, would be to increase the effective area. If the light travels along an optical fiber, a large number of turns can be used for that purpose - as we shall see in the next sections. In any case, the Sagnac effect has to be greatly enhanced in order to allow the design of a practical rotation sensor, with good enough sensitivity and compactness.

1.5 Reciprocity

It is very important to point out here the fact that the Sagnac effect is a nonreciprocal effect. The principle of reciprocity applies to many physical phenomenon. A reciprocal device, is such where you cannot tell weather one propagates through it in either a direct or reverse direction. In the case of Sagnac effect, the rotation simply orients the experiment environment and makes it different from its mirror image - the sign reversal of the phase shift is associated with the reverse direction of propagation. Luckily, as we shall further on see, many factors of noise in the system tend to be reciprocal in nature. That way, such effects cancel each other (when taking into account both propagation directions, while the Sagnac effect doubles. Effects which can act in a non-reciprocal way, such as the uneven thermal expansion that we shall describe further on, become parasitic effects which are very difficult to eliminate.

Chapter 2

The Ring Laser Gyroscope (RLG)

2.1 General Description

The Ring Laser Gyroscope (RLG) was first developed in the 1960's. The major concept was to introduce a laser cavity into the light path, in order to increase the strength of the Sagnac effect. This device is built as a resonator, and the light circulates the closed path many times as the system resonance is being created. The ring laser gyroscope is basically an 'active' approach to build an optical gyroscope, due to the introduction of the active laser. That is the reason it is sometimes called an active ring resonator. The basic configuration of the laser cavity appears in figure [2.1]: an active laser medium is introduced into a closed cavity. The cavity consists of totally reflecting mirrors, and an output mirror with small transmissivity. Two beams originating at the active laser propagate in two opposite directions. A fraction of the power of both beams is emitted through the output mirror into a detector.

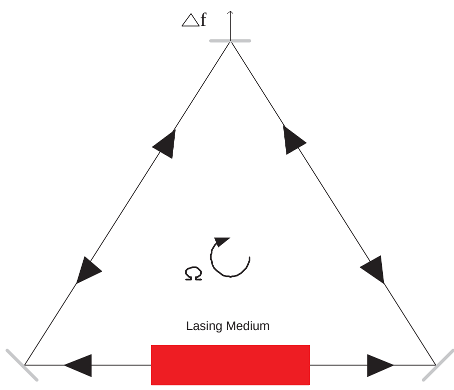

Figure 2.1: Ring Laser Cavity

When the resonator is at rest, both beams travel through the same optical path and their frequencies are the same. However, when the resonator is rotating, each beam sees a different cavity length due to the Sagnac effect. Therefore there is a frequency difference between the two beams. This frequency can be calculated as follows: We shall first extract the change in wavelength from the optical path difference. Let the number of periods in the ring be $\frac{P}{\lambda}$ where P is the perimeter of the ring. We can divide the total optical path difference by the number of periods, to obtain the additional length each period accumulates:

$$\Delta\lambda = \Delta L \frac{\lambda}{P} = \frac{4A\Omega\lambda}{cP} \tag{2.1}$$

Where we used equation (1.2), with A as the total ring area and Ω as the rotation velocity. The difference in frequency can now be easily obtained:

$$|\Delta f| = \frac{c}{\lambda^2}\Delta\lambda = \frac{4A\Omega}{P\lambda} \tag{2.2}$$

This frequency shift results in a time varying phase shift between the two output beams. Their interference pattern is therefore modulated by a beat frequency which equals Δf, and can be written as follows:

$$I = I_0\left(1 + cos(2\pi\Delta f t)\right) \tag{2.3}$$

The number of beat periods can now be counted in order to measure the total rotation of the system. The angle which corresponds to a single beat period is obtained by multiplying the rotation velocity Ω by the beat period. This angle is called the angular increment and can be written as:

$$\Theta_{inc} = \Omega T_{beats} = \frac{\Omega}{\Delta f} = \frac{\lambda P}{4A} \tag{2.4}$$

The total amount of rotation is easily obtained by multiplying the number of beats in the angular increment defined above.

2.2 Some Typical Numbers

Let us assume a laser with a wavelength of $633nm$ (a Helium Neon laser), and a triangular ring with a side of length $10cm$. The area of the ring A is therefore $45cm^2$. The perimeter will be $30cm$. We shall again take the earth rotation velocity $\Omega_E = 7.3 \times 10^{-5}\frac{rad}{sec}$. Using equation (2.2) we can see that the beat frequency is:

$$\Delta f = 7Hz \tag{2.5}$$

This beat frequency can be easily measured by simple electronic means. We can calculate the angular increment using equation (2.4). We obtain:

$$\Theta_{inc} = 1.04 \times 10^{-5} rad \tag{2.6}$$

2.3 Mode Locking

One of the major difficulties in the implementation of a ring laser gyroscope, is the phenomenon of mode locking. When the two counter-rotating beams get too close in frequency they can get locked together and oscillate in the same frequency. Mode locking happens when there is some sort of weak coupling between the two modes - such coupling can be caused due to backscattering of the reflecting mirrors. In that case, if the beat frequency gets smaller than some certain threshold - the beat noise can be eliminated and we can no longer sense the rotation. Since the beat frequency is proportional to the rotation velocity, this phenomenon enforces a practical limit over the measurement sensitivity. Different methods to improve this limit were developed throughout the years. The most obvious approach was an improvement in the reflective coating of the mirrors, but this still limits the sensitivity to around 10 deg/hour. Another approach was to use mechanical rotation of the gyroscope, which shifts the measuring scale away from the mode locking threshold. Such methods can increase the sensitivity of the device to around 10^{-2} deg/hour. Other advanced techniques are also used to increase sensitivity even further. The world's largest laser gyroscope, with an effective area of $1m^2$ was built in Canterbury, New Zealand, is shown in figure 2.2. This laser reaches an extraordinary sensitivity of 10^{-7}(!) earth rotations - around 10^-6 rad/hour. This sensitivity is so great that it is enough to observer the daily effect of the moon over the earth's rotation axis.

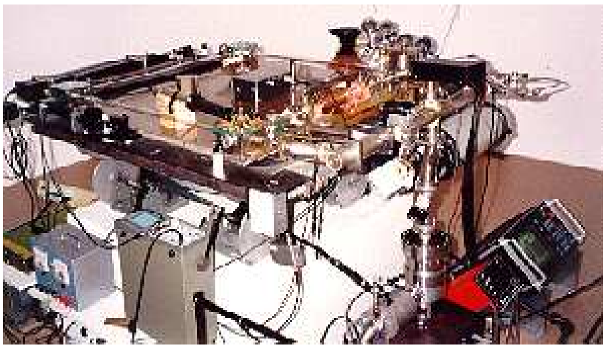

Figure 2.2: Canterbury laser gyroscope

The ring laser gyroscope technology is a mature technology, and is being widely used mainly in inertial navigation systems (INS). However, the products are still complex and expensive. As we shall further on see, the introduction of fiber optics into the game, can provide several important advantages.

Chapter 3

The Interferometric Fiber Optic Gyro (I-FOG)

3.1 General Description

In the I-FOG, an optical fiber is used as the medium of propagation for the light. A long fiber cable is winded into loops in order to increase the effective area of the system, as shown in figure 3.1. Two beams are again propagating through the fiber in opposite directions. It is interesting to look at the analogy to a coil: similar to the fact that the magnetic flux in a coil grows in proportion to the number of turns, and hence the induction of the coil is increased, the Sangac effect is increased by the number of terns in the optical fiber. We have seen in equation (1.5) that the Sagnac effect is proportional to the flux of the rotation vector through the closed light path. Due to the development of low loss optical fibers, the effect could be greatly enhanced using long optical fibers, so that a resonance cavity is no longer required. If we have an optical fiber with N loops and diameter D for each loop, then according to equation (1.3) the phase difference between the two counter rotating beams would be:

$$\Delta\phi = \frac{2\pi LD}{\lambda c} \tag{3.1}$$

Where L is the total length of the fiber which is: $L = N\pi D$. This phase difference can now be measured in simple interferometric means. The intensity of light at the output of the system is modulated by the phase difference between the two beams as follows:

$$I = I_0 \left(1 + cos(\Delta\phi)\right) \tag{3.2}$$

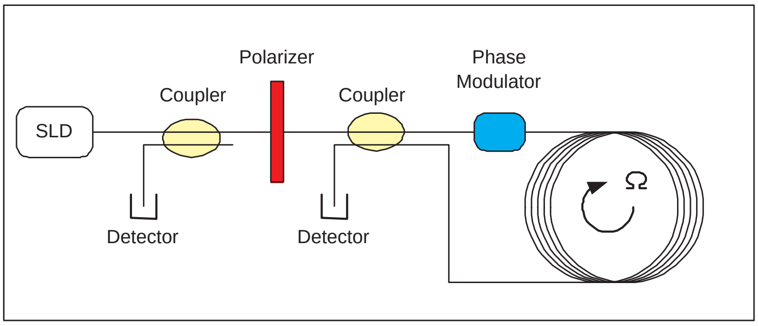

Figure 3.1: Elementary configuration of an I-FOG

The elementary configuration of the I-FOG is shown in figure 3.1. In order to reduce parasitic noise (as we shall explain in the next sections) a low coherence light source (such as a semiconductor superliminescent diode - SLD) is used. In order to be able to determine the rotation rate from a very small phase difference, both light beams must travel in the fiber in exactly the same path and propagation mode (maintaining reciprocity). So the first practical consideration would be to use a single mode fiber. In fact, even at rest, there is some difference between the two waves due to different propagation delay for each polarization state, which results in a bias fluctuation. In order to solve this problem, a polarizer is used (figure 3.1), ensuring the two waves have exactly the same polarization. figure 3.1 shows two couplers and two detectors. Since the transmission and coupling characteristics of a fiber coupler are different, both waves must experience these two characteristics in the same manner - this is the reason two couplers are present. The two detectors can now measure both waves in a 'reciprocal' manner. The phase modulator which appears in the figure is used in order to create a bias phase difference of $\pi/2$ between the two beams. This is in order to increase the sensitivity of the measurement - without this phase shift, the signal at the detector has zero gradient at $\Omega = 0$. The phase shift puts the signal in a position with high gradient at $\Omega = 0$ which provide a better measurement resolution, as shown in figure 3.2. In that case, the intensity at the detector in equation (3.2) changes to:

$$I = I_0 \left(1 + cos(\Delta\phi) - \frac{\pi}{2}\right) \tag{3.3}$$

3.2 Dynamic Range and Typical Numbers

A phase difference can be measured up to an ambiguity of $\pm\pi$ around zero. Therefore, we can define the operating range of the gyroscope by a rotation velocity Ω_π

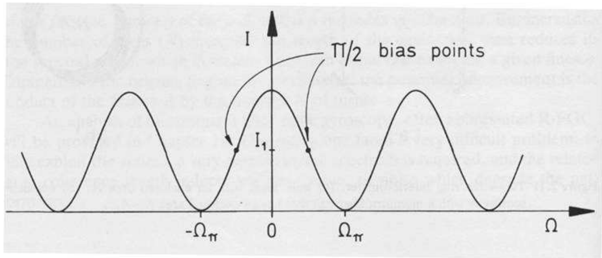

Figure 3.2: Response of an I-FOG

which results in a phase shift of π as follows from equation (3.1):

$$\Omega_\pi = \frac{\lambda c}{2LD} \tag{3.4}$$

Usually, a phase difference of 1 μrad is a reasonably measurable quantity, so we can also define Ω_μ as the rotation velocity which corresponds to such phase difference:

$$\Omega_\mu = \frac{\Omega_\pi}{\pi 10^{-6}} \tag{3.5}$$

Since Ω_π is inversely proportional to the total length of the fiber, and to the diameter of each fiber loop, the dynamic range of the device can be easily configured by changing those two parameters. For example, in order to increase the dynamic range of the device one can simply reduce the effective fiber area. On the other hand, in order to get a higher sensitivity with a lower dynamic range, one needs to increase the effective fiber area. This is a great advantage, since these parameters are easily controlled and without the need to actually redesign the device, any required operating range can be achieved. As a numerical example, let's assume that we have a fiber coil of length $L = 1km$ and diameter $D = 0.1m$. Taking a typical wavelength of $850nm$ we can find out that Ω_π is around 1.3 rad/sec, or 73 deg/sec, and that case, Ω_μ will be 0.085 deg/hour. On the other hand, if we reduce the fiber length to $L = 100m$ and take a diameter of $3cm$ we get Ω_π to be 2400 deg/sec and Ω_μ will be 2.8 deg/hour.

3.3 Fundamental limitations of the I-FOG

The theoretical sensitivity of the fiber optic gyroscope is determined by the photon shot noise, which emerges from the statistical distribution of the energy of the photons that hit the detector. The formula describing the change in the measured angular velocity for the I-FOG due to photon shot noise is given by:

$$\Delta\Omega = \frac{c\lambda}{2LD\sqrt{n_p}\eta_D\tau} \tag{3.6}$$

Where L is the fiber length, D is the diameter of each turn, η_D is the detector's quantum efficiency, n_p is the number photons hitting the detector per second, and τ is the averaging time on which the intensity measurement is taken. The number of photons n_p is directly related to the measured power P using:

$$n_p = \frac{P\lambda}{hc} \tag{3.7}$$

Where h is Plank's constant. As an example, we can take our previous case of a fiber coil of length $L = 1km$ and diameter $D = 0.1m$, with a wavelength of $850nm$. We assume a quantum efficiency $\eta_D = 0.3$ and an averaging time of $\tau = 1sec$. We take a typical power of $P = 1mw$, which is equivalent to a number of $n_p = 4.3 \times 10^{15}$ photons/sec using equation (3.7). The result is: $\Delta\Omega = 3.6 \times 10^{-8}$ rad/sec, which is 0.0075 deg/h. If we look back at our previous result for this specific case of Ω_{mu} =0.085 deg/h we see that the photon noise limit in this case is quite good. At the same time, the power received at the detector decreases exponentially with fiber length so that:

$$P = P_0 e^{-\alpha L} \tag{3.8}$$

Where P_0 is the input power and α represents the fiber's attenuation per unit length. So in that case, the photon noise, being inversely proportional to the square root of the power received at the detector, increases with fiber length. On the other hand, we saw previously that the Sagnac effect increases with the effective area of the light path - i.e. with the cable length - so these two effects compete. This implies that for a given sensitivity and fiber, there is always an optimal fiber length which we are ought to use. Practically, these optimal values are too high - for example: Let us take a silica fiber corresponding to a wavelength of $\lambda = 850nm$, which has a typical attenuation factor of $\alpha = 2db/km$. Calculation of the optimal length yields $L = 4km$. Typically, coil lengths in commercial products do not get higher than 1km, or they would become too large to fit within reasonable overall dimensions, or simply too expensive.

3.4 Noise Factors in the I-FOG

We will now present several noise factors which influence the performance of the I-FOG and discuss the countermeasures taken to prevent them.

3.4.1 Backscattering

Rayleigh backscattering is the dominant noise in the I-FOG. It is caused when backscattering or reflections of one light wave in the fiber interfere with the other light wave moving in the opposite direction. This interference acts as a noise source to each light beam. In order to reduce this effect, a low coherence light source (such as an SLD) is used. What happens is that since the coherence length of the source is only several tens of microns, only reflections or backscattering from a very small area (near the middle of the sensor) can actually cause interference. The usage of an SLD therefore reduces this effect significantly.

3.4.2 Optical Kerr Effect

The optical Kerr effect is a change in the refractive index of the fiber's core material due to the intensity of the traveling light wave. The change is proportional to the intensity of the light wave. An imbalance, therefore, between the intensities of the rotating and counter-rotating waves, can cause a phase shift between the two waves which can disturb the actual phase difference measurement. A 50 percent imbalance of intensities would result in a rotation rate error of around 10 deg/h! An intensity ratio of 10^{-4} can lead to a 10^{-3} deg shift. A bias phase shift in the gyroscope must be induced in proportion to intensity imbalance. Changes in intensity balance, however, are not constant and can cause a drift in the measurement result. The correct approach to solve this problem would be to look at the two components of this effect: The self-phase modulation - Kerr effect caused by the intensity of the wave upon itself ; and the cross-phase modulation - Kerr effect caused by the intensity of one wave upon the other (the counter rotating wave). It was found that these two effects cancel each other when the light source has low coherence. So again, in a similar manner to the approach taken to solve backscattering, a low coherence light source can reduce the optical Kerr effect as well.

3.4.3 Uneven Thermal Fluctuation

This is probably the major barrier in the making of high precision I-FOGs. The index of refraction of the optical fiber is a function of temperature. Hence a light wave traveling throughout the fiber can experience propagation delay due to a change in temperature along the fiber - as it travels from one point at a certain time and a certain temperature, to another point at another time and another temperature. This propagation delay will most likely be different for the co-rotating wave and the counter-rotating wave, if the temperature distribution along the turned fiber is not symmetrical with respect to the center of the fiber. Both waves will experience different phase changes for their complete propagation along the optical fiber, which will result in an output error. There are several approaches to reduce this noise factor. First, one should consider choosing a fiber with a low temperature coefficient (low dependence of the index of refraction in the temperature). But even small temperature changes can cause significant drifts in the rotation rate measurement. A more effective approach is to develop unique winding technologies which ensure that all portions of the turned fiber, which are located at symmetrical positions with respect to its center, lie side by side. Using this approach, the temperature gradient is symmetrical with respect to the center of the fiber. Another solution, is the obvious technique of monitoring the temperature along the fiber and compensating for the effect at the gyroscope's output. The best performance so far with practical I-FOG's is of approximately 0.01deg/h sensitivity, which is limited mainly by the uneven thermal fluctuation.

3.4.4 Polarization and Birefringence

We have previously mentioned the polarization problem in the I-FOG, caused by the different propagation delays of each polarization mode. A single mode fiber still allows transmission of two orthogonal polarizations so it does not completely eliminate this difficulty. This problem is mainly influenced by the phenomenon of Birefringence. Birefringence is an optical phenomenon where light is transmitted at slightly different velocities depending on the angle of incidence. Also, it describes light scattering due to different refractions created by impurities, defects, or stresses within the fiber material. Mechanical stresses, therefore, can introduce significant power transfer between polarization and birefringence. The interference signal between the two polarizations can then lead to actual fading of the detected light power. This can result in either output drift or a reduction in signal to noise ratio. In fact, sometimes, the signal can simply disappear. We have introduced the use of a polarizer in order to suppress one polarization and reduce the polarization-birefringence noise. However, such technique does not completely solve the problem. In order to decrease this effect and increase the sensitivity of the gyroscope, a PM (polarization maintaining) fiber is used with high birefringence. When using such a fiber, the unwanted polarization mode is not significantly excited. The two polarization modes in the fibers then have different propagation constants, so that the unwanted polarization mode has a much larger delay compared with the desired mode. This way the unwanted mode cannot interfere with the desired one, and the sensitivity can be increased. The weak polarization mode is almost completely suppressed, and the fading phenomenon disappears.

Chapter 4

Applications of Optical Gyroscopes

Fiber optic gyroscopes have long ago passed the turning point of meeting the performance limits required for practical applications. Due to the fact that they have several great advantages over the traditional spinning mass gyros, in many applications the optical gyroscopes have replaced the old types. Moreover, those advantages have already created new fields of applications for gyroscopes. The optical gyro has a very short warm up time relative to the rotating mass gyro. This way it can be switched on and off instantly, which can result in much lower power consumption. A lower power consumption is also due to the fact that an optical gyro does not require a mechanical engine. It has a much lighter weight, it is maintenance free and has reliable operation due to its non mechanical nature. As we have seen, it can present a high dynamic range and a large bandwidth. Last, and perhaps the most important advantage, is the fact that it can be made at low cost, especially for those applications that do not require high sensitivity. Rotation sensors are commonly divided into 3 main grades, based on the required sensitivity of the application in which they are installed:

- Moderate grade - up to 200 deg/hour
- Intermediate grade - up to 1 deg/hour
- High grade - up to 0.01 deg/hour

Figure 4.1 presents graphically the required sensitivities for some typical gyro applications. Only a fraction of the existing and potential applications are shown in the figure, but the diversity, both in fields of use and sensitivities is clearly seen. Figure 4.2 shows a commercial moderate grade I-FOG product which is available in the market, found using a simple internet search.

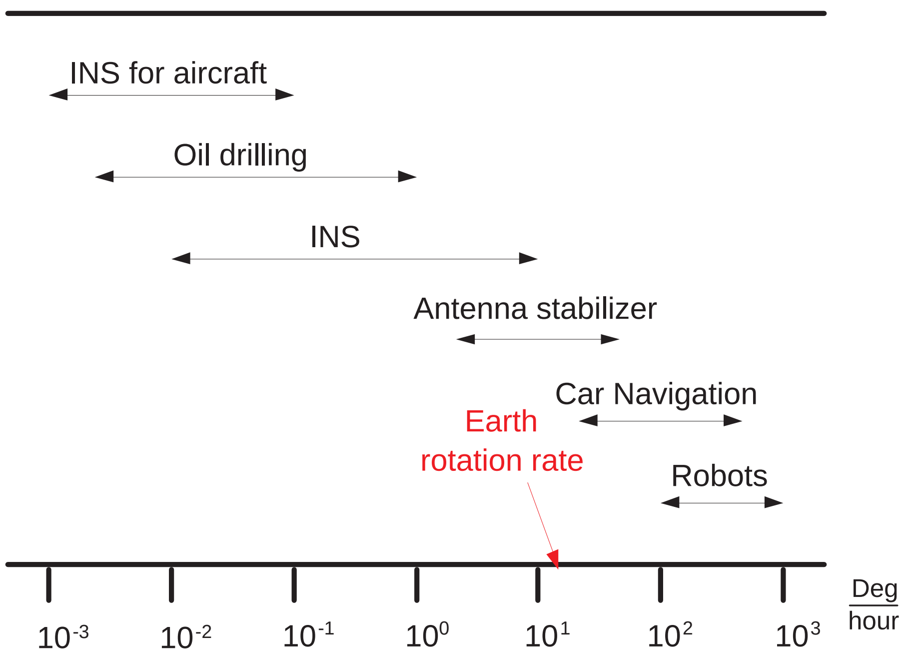

Figure 4.1: Typical applications and required sensitivities

Figure 4.2: A commercial I-FOG

The most commercially popular applications in the moderate range nowdays are the automobile navigation systems. The advanced models of automobile navigations these days include a gyro in addition to the GPS (global positioning system). The gyro acts as the main sensor of the system and the GPS only corrects the data occasionally in case of an unlikely error. The I-FOG also operates when the GPS does not work, or when map information is missing. This system enables accurate navigation in complicated roads and paths. The market for this product is as large as several dozens of millions of products per year. Among the moderate and intermediate range applications are also antenna stabilizers, which help maintaining narrow beam wireless links which are sensitive to tiny mechanical movements. Camera stabilizer is another important and popular application. One of the most common applications for a camera stabilizer is one that enables filming smooth TV pictures from a moving helicopter. Another type of applications are navigation systems for unmanned vehicles, such as cleaning robots, forklifts, and dump trucks which need to operate in hazardous environments. Other applications include crane controllers, a north finder (compass), control and navigation of agricultural machines, motion monitoring of trains, automobiles and even the human body. Inertial navigation systems for spacecraft, aircraft or ships are among the moderate and high grade applications, as well as motion control detectors for oil drilling facilities. In 1991 the first I-FOG in space was used in Japan for the navigation of an experimental space rocket. Perhaps the most known usage of optical gyroscopes is its application in the Boing 777 aircraft. The plane's inertial navigation system now uses six ring laser gyroscopes of 0.01 deg/hour sensitivity, and four intermediate grade I-FOG's.

Chapter 5

Future Generation of Optical Gyroscopes

5.1 The Resonance Fiber Optic gyro (R-FOG)

As shown before, current high grade I-FOG's exhibit sensitivities of up to 0.01 deg/hour. Ring laser gyros, on the other hand, which can exhibit higher sensitivity, are complex and expensive. The resonant fiber optic gyroscope (R-FOG) is a passive resonator approach which combines both worlds. A passive ring cavity built using an optical fiber is used instead of the active cavity used in the laser gyro. The usage of a passive cavity eliminates the problem of mode locking in laser gyros. Figure 5.1 shows the basic configuration of an R-FOG. As shown in the figure, a much shorter length of fiber (relative to the I-FOG) is used. The structure is in fact a ring resonator with very high finesse. Due to the Sagnac effect, the resonance frequency of the R-FOG is changed during rotation. The rate of change of the resonance frequency is similar to that obtained for the laser gyro (see equation (2.2)). The resonance frequency appears as a strong peak in the output response curve. Due to the large Q factor of the resonance, the response peak is very sharp, and a much higher sensitivity than that of the I-FOG can be achieved. In fact, it was shown that a fiber of length 10cm is potentially enough for building a high grade gyroscope which can be used for aircraft navigation. The usage of short fiber, can also reduce the uneven thermal fluctuation, which is the major noise factor in I-FOGs, due to the fact that it enables to easily reach symmetry in the system. In addition to that, the usage of a short fiber can potentially reduce the cost of the device, although it requires a more expensive polarization maintaining fiber. Unlike the I-FOG, the light source should be very highly coherent with a much higher wavelength stability. Mainly due to the difference in the nature of the light source characteristics, the noise factors in R-FOGs have different behavior than those in the I-FOG. As far as the writer of this paper understands, this gyro is now in advanced research stages, but still has not reached a significant commercial status.

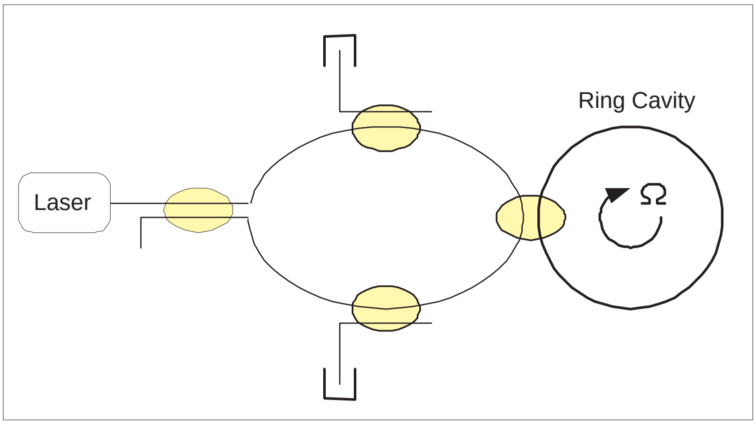

Figure 5.1: Resonator fiber-optic gyro (R-FOG) elementary configuration

5.2 A Photonic Crystal Based Gyro

Lately, it has been suggested (see [4]) by prof. B.Steinberg of Tel Aviv university, to use a photonic crystal as a medium to build compact optical gyroscopes. Photonic crystals are considered a 'hot' topic in physics during the past two decades, and are studied mainly for their potential to build optical components which can be integrated with standard semiconductor technology. In general, a photonic crystal is a periodic structure of at least two materials with different electromagnetic properties (mainly different dielectric constant). A practical example is a silicon 2D slab, with holes drilled in a 2D periodic array, with typical distance of the order of magnitude of a light wavelength (μm). Such structures have been shown to exhibit frequency band gaps - they can be totally transparent to electromagnetic radiation, but totally block radiation in a wavelength interval inside the specific band gap of the photonic crystal. It has been shown, that by applying defects to such structures (for example, removing a hole) resonance microccavities with high Q, carrying resonance frequencies within the crystal band gap, can be created and trap light. An interesting mechanism called coupled-cavity waveguide (CCW) can now be realized for light guiding inside the photonic crystal: the CCW is a linear array of equally spaced identical local defects. When a set of microcavities is situated along such an array, signal propagation of light along the CCW can be based on tunneling of light from one cavity to the next. The propagation modes of such CCW posses a very narrow band. Such CCW can now be built inside the photonic crystal in a circular path, or a ring shape, to form a ring resonator CCW (RR-CCW). Figure 5.2 shows an example for such ring resonator. The transparent circles in the figure represent holes in the silicon slab, and the black circles represents defect in the structure, which can be simply 'missing' holes. Building a photonic crystal gyroscope has an extraordinary potential. A highly sensitive gyro can be built with an effective area of not more than a few square millimeters. The cost advantage is also very large - fabrication of photonic crystals can be done using standard semiconductor fabrication equipment. The concept of photonic crystal as a medium for compact optical gyroscopes has been proven theoretically, and numerical simulations are now being studied in order to understand the different design parameters. The writer of this paper is now working such numerical simulations as part of his Master's thesis.

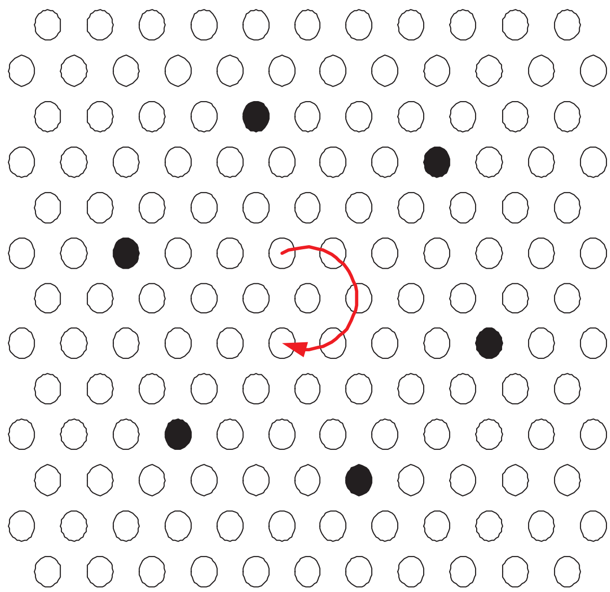

Figure 5.2: A ring resonator in a photonic crystal

Summary

The theoretical background of the Sagnac effect, for the design of optical rotation sensors had been described. The small scale of the effect was calculated in order to emphasize the difficulties in designing sensitive gyros. The ring laser gyroscope technology was described. It was shown, that although the RLG is a mature and superiorly accurate technology, its complexity and cost are not suitable for production in commercial quantities. A more practical approach for commercial products, in the form of the interferometric fiber optic gyro (I-FOG) was described in details. Various noise factors limiting the sensitivity of the fiber optic gyro were explained, together with the countermeasures taken for their elimination. It was shown that due to several effects, the sensitivity of I-FOG's is still limited, although it is fairly good for its usage in many applications, and especially due to its advantages over traditional spinning mass gyros. Various commercial applications of optical gyros were presented and classified according to their required sensitivities, and the large scale of both the current and future markets for this product was emphasized. Finally, new approaches such as the resonance optic fiber gyro, and the photonic crystal ring resonator were presented as a briefing of the future possibilities and research, which still lie ahead in this important subject.

Bibliography

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