Chapter 5
Gyroscope technology 2

5.1 Optical sensors

5.1.1 Introduction

This term is applied to those classes of gyroscope which use the properties of electromagnetic radiation to sense rotation. Such devices often use the visible wavelengths, but it is also possible to operate in the near infrared. Some mechanical gyroscopes use optical angle pick-off sensors, but for this discussion they are not classed as optical gyroscopes. Optical gyroscopes use an interferometer or interferometric methods to sense angular motion. In effect, it is possible to consider the electromagnetic radiation as the inertial element of these sensors.

It was during the late nineteenth century that Michelson pioneered work with optical interferometers, although his goal was not to produce an optical gyroscope. In 1913, the Sagnac effect was reported [1] and this is the fundamental principle on which optical gyroscopes are based. When light travels in opposite directions (clockwise and anti-clockwise) around an enclosed ring, differences arise in the apparent optical length of the two paths when the ring is rotated about an axis orthogonal to the plane containing the ring. In 1925, this concept was applied by Michelson and Gale [2] in Chicago using a ring gyroscope with a perimeter of over one mile. By sending ordinary light through evacuated water pipes, they were able to detect the shift produced by the rotation of the Earth.

Further impetus to produce an optical sensor resulted from the demonstration of a laser by Maiman in 1960 [3]. These devices produce a well collimated and highly monochromatic source of electromagnetic energy between the ultraviolet and far infrared part of the spectrum, the wavelength being determined by the laser medium. In 1963, the first ring laser was demonstrated by workers at Sperry Gyroscope [4]. This marked the beginning of the development of the ring laser gyroscope. About a decade later the fibre optic gyroscope was first demonstrated [5].

Clearly, the history of the development of optical gyroscopes is far more recent than the history of the mechanical sensors. Further impetus for the development of these sensors, besides the development of the laser, was the interest in the application of strapdown technology and the desire to capitalise on the benefits anticipated from the use of solid-state inertial sensors. One of the main difficulties in the application of strapdown technology from the point of view of gyroscope performance was the lack of adequate dynamic range of the mechanical sensors for the more accurate applications. Initial estimates of performance suggested that the ring laser gyroscope could provide the solution.

The spectrum of performance of optical gyroscopes ranges from the very accurate with bias of less than 0.001°/h, usually ring lasers, to tens of degrees per hour, often from the simpler fibre optic gyroscopes. Hence the range covered by the optical devices is very similar to that covered by the mechanical gyroscopes. Generally, all the types of optical gyroscopes are suitable for various strapdown applications, depending of course on the demanded accuracy of the system.

It appears that the application of optics to the sensing of angular rate can offer a number of advantages over the use of the well-established mechanical technology. Some of the advantages often cited are listed below:

1. wide dynamic range;
2. instant start-up;
3. digital output;
4. output independent of some environmental conditions (acceleration, vibration or shock);
5. high rate capability;
6. easy self-test;
7. system design flexibility;
8. extended running life.

5.1.2 Fundamental principles

Optical gyroscopes rely upon the detection of an effective path length difference between two counter-propagating beams of light in a closed path. The mathematical development given here shows how this path difference arises in the presence of an applied turn rate about an axis perpendicular to the plane containing the light path.

Consider a perfect stationary circular interferometer with the light constrained to travel around the circumference of a circle of radius R as shown in Figure 5.1. Light enters the 'ring' at the point X, where there is a beam splitter which directs two beams of light in opposite directions around the complete ring, these beams recombining later at the beam splitter. The transit time (t), the time for the light to make one complete pass around the ring whilst the ring is stationary, is identical for both beams and is given by:

$$t = \frac{2\pi R}{c} \tag{5.1}$$

where c is the velocity of light, which is considered to be invariant.

However, when the interferometer is rotated with angular velocity Ω, the time for each light beam to pass around the circumference is modified. This is because of the

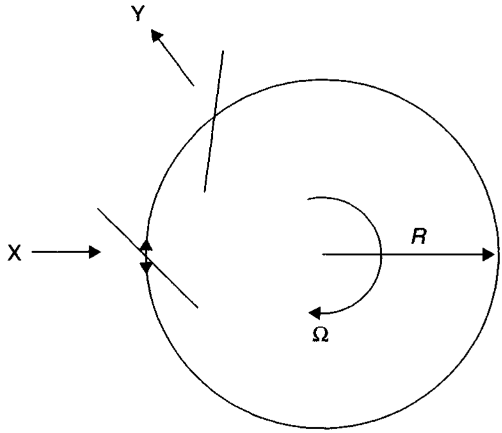


Figure 5.1 Circular rotating (Sagnac) interferometer

motion of the beam splitter during the time taken for the light to pass around the ring. As shown in the figure, the beam splitter will have moved to position Y. Therefore, light travelling in a clockwise direction will have to travel further than the distance travelled when stationary. The converse is also true for the anticlockwise beam. More generally, with respect to inertial space, light travelling with the direction of rotation must travel further than when the interferometer is stationary. Light travelling against the direction of rotation will have its path length reduced when compared with the stationary condition. Hence, the single pass transit time for the two beams is given by the following equations.

$$\begin{aligned} &\text{Clockwise path,} \qquad && t_1 = \frac{2\pi R + \Delta L_+}{c} \\ &\text{Anti-clockwise path,} \qquad && t_2 = \frac{2\pi R - \Delta L_-}{c} \end{aligned} \tag{5.2}$$

Now, $\Delta L_+ = R\Omega t_1$ and $\Delta L_- = R\Omega t_2$ are the increment and decrement in the path length respectively. As reported by Aronowitz [6], this can also be interpreted as the velocity of light being different for the two counter-propagating beams and the path length being invariant.

From the above equations, the difference in transit time, Δt, is given by:

$$\Delta t = t_1 - t_2 = 2\pi R\left[\frac{1}{c - \Omega R} - \frac{1}{c + \Omega R}\right] \tag{5.3}$$

To first order approximation, this becomes:

$$\Delta t = \frac{4\pi R^2 \Omega}{c^2} \tag{5.4}$$

The optical path length difference $\Delta L = c\Delta t$, and may therefore be expressed as:

$$\Delta L = \frac{4\pi R^2 \Omega}{c} \tag{5.5}$$

The area (A) enclosed by the path length is πR^2. Hence, the above equation may be rewritten as follows:

$$\Delta L = \frac{4A\Omega}{c} \tag{5.6}$$

Aronowitz [6] gives a more rigorous equation for the difference in closed path transit time for counter-propagating light beams on a rotating frame. This is based on the loss of synchronisation between a clock travelling on a rotating reference frame compared with one on a stationary reference frame. The conclusion from this study is that the optical path difference, $4A\Omega/c$, is independent of the position of the axis of rotation. As noted by Aronowitz, measurement of the optical path difference enables an observer, located on a rotating reference frame, to measure the so-called absolute rotation of his reference frame.

The various optical sensors described below rely on generating a path difference in an interferometer, the major differences being in how the light is generated and how the path difference is 'observed'.

5.1.3 Ring laser gyroscope

5.1.3.1 Introductory remarks

As stated above, serious development started in the early 1960s. The first ring laser gyroscopes were large and somewhat delicate. Substantial investment has led to the production of very compact devices that produce extremely low bias, of 0.001°/h or better. Typical path lengths for the accurate sensors are about 300 mm. Very small laser gyroscopes have also been produced with a path length of about 50 mm. Generally, these small sensors have a bias in the region of 5°/h. Currently, the more accurate gyroscopes are used in strapdown navigation systems in commercial aircraft as well as in military fixed and rotating wing aircraft.

5.1.3.2 Principle of operation

Operation of a ring laser gyroscope relies on the fact that an optical frequency oscillator can be assembled as a laser using three or more mirrors to form a continuous light path. Typically, three mirrors are used to form a triangular shaped light path. If a light beam is generated at any point on this path, it can travel around the closed path, being reflected in turn from each mirror, to arrive back at its starting point. Sustained optical oscillation occurs when the returned beam is in phase with the outgoing beam. Two such travelling wave laser beams are formed independently, one moving in a clockwise direction and the other in an anti-clockwise direction.

When the sensor is stationary in inertial space, both beams have the same optical frequency. However, when the sensor is rotated about the axis perpendicular to the plane containing the light beams, changes occur in the optical path lengths of the two beams. The frequency of each beam changes to maintain the resonant condition required for laser action such that the frequency of the beam with the longer path length decreases whilst the frequency of the other beam increases. This path difference is very small, no more than 1 nm, thus a source with high spectral purity and stability, such as a helium–neon gas laser, is required to make the laser gyroscope concept feasible.

Maintenance of laser action requires a constant phase at a given mirror surface after every round trip in order to maintain the resonant condition.

Hence, if L_a is the anti-clockwise path length and L_c the clockwise path length, then the resonant condition is given by:

$$\begin{aligned} L_a &= p\lambda_a \\ L_c &= p\lambda_c \end{aligned} \tag{5.7}$$

where p is the mode number, typically of the order of a million, and λ_a and λ_c are the two wavelengths of laser energy. When this interferometer is rotated at a rate Ω, these path lengths differ and are given by:

$$\begin{aligned} L_a &= p\lambda_a = L + \frac{2A\Omega}{c} \\ L_c &= p\lambda_c = L - \frac{2A\Omega}{c} \end{aligned} \tag{5.8}$$

where L is the perimeter length and the path difference $\Delta L = 4A\Omega/c$.

Now if ν_a and ν_c are the optical frequencies of the two beams, $\nu_a\lambda_a = \nu_c\lambda_c = c$. Substituting for wavelength in the above equations, we have,

$$\nu_a = \frac{cp}{L_a} \quad \text{and} \quad \nu_c = \frac{cp}{L_c} \tag{5.9}$$

Hence, small changes in path length result in small changes in frequency, $\Delta\nu$, given by the relation,

$$\frac{\Delta\nu}{\nu} = \frac{\Delta L}{L} \tag{5.10}$$

Substituting for ΔL in this equation, this beat frequency can be expressed as:

$$\Delta\nu = \frac{4A\Omega}{cL} \quad \nu = \frac{4A\Omega}{L\lambda} \tag{5.11}$$

where

$$\lambda = \frac{\lambda_a + \lambda_c}{2} \quad \text{and} \quad \nu = \frac{\nu_a + \nu_c}{2} \tag{5.12}$$

It follows from eqn. (5.11) that the turn rate (Ω) may be determined from the frequency difference ($\Delta\nu$) generated in its presence. The scale-factor of the sensor is directly proportional to the area (A) enclosed by the optical path. Changes in A result from variations in the cavity length. Use of active laser gain control and cavity path length control usually contain these excursions to a few parts per million or less for most designs.

Substitution of typical values into eqn. 5.11 shows the beat frequency to be from a few hertz up to megahertz. This beat frequency can be detected, even for very slow rotation rates. As noted by Aronowitz, thermal and mechanical instabilities can cause frequency variations in the individual beams that are far greater than the rotational beat frequency, as can be deduced from eqns. (5.9)–(5.11). The successful operation of this type of sensor is achieved since both beams occupy the same laser cavity and therefore are subject to identical perturbations.

In order to detect the rotational motion, a small amount of light from each beam is allowed to 'escape' through one of the mirrors, known as the output mirror, and the two beams are combined using a prism to form an interference pattern on a set of photo-diodes. The frequency difference between the two beams causes the interference fringes to move across the detectors at a rate equal to the difference in frequency between the two beams which is also proportional to the rotational motion.

Hence, the movement of a single fringe past the detector corresponds to an incremental rotation, $\Delta\theta$, where,

$$\Delta\theta = \frac{\lambda L}{4A} \tag{5.13}$$

This equation can be used to determine the sensitivity of a ring laser gyroscope. For a device having an equilateral triangular path of total length L, the area is given by:

$$A = \frac{1}{2}\left(\frac{L}{3}\right)^2 \sin 60^\circ \tag{5.14}$$

Substituting in the preceding equation, it can be shown that the sensitivity is inversely proportional to the path length, viz.

$$\Delta\theta = \frac{3\sqrt{3}\,\lambda}{L} \tag{5.15}$$

For instance, considering a helium–neon laser in which the optical wavelength is 0.6328 μm (632.8 nm), the sensitivity of a 30 cm path length device is 2.25 arcs per fringe. For the smallest ring caser gyroscope, with a 50 mm path length, the sensitivity is 13.5 acrs per fringe.

5.1.3.3 The lock-in phenomenon

At very low rotation rates, the two laser beams in the cavity cease to oscillate at different frequencies and assume the same frequency, or 'lock together'. The interference pattern does not change so there is no output signal. This phenomenon of frequency synchronisation is illustrated in Figure 5.2 and is known as the lock-in condition, or simply lock-in. It is analogous to the mutual coupling common in electronic oscillators working in close proximity at similar frequencies. In the optical case, it is caused by the radiation of one laser beam being scattered into the other beam causing the host mode to change frequency towards that of the back scattered energy, with the consequence of both beams being shifted to the same frequency. There are many sources of back scattering, but careful design and the use of very high quality mirrors allows the effect to be minimised and the lock-in condition is restricted to a very narrow zone close to the zero rotation rate.

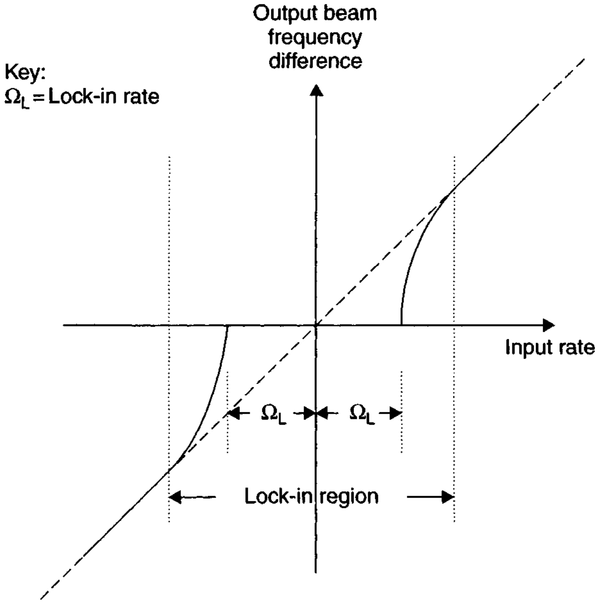


Figure 5.2 Laser gyroscope input/output characteristic

Alleviation of lock-in

One of the most common methods used to alleviate the lock-in problem is the use of mechanical oscillation. Mechanical dithering consists of applying angular vibrations to the entire cavity at high frequency but at low amplitude and through small angles, thereby avoiding low frequency outputs. Through the use of a so-called large dither product (dither frequency multiplied by the amplitude), having a high frequency motion but small displacement, very little time is spent by the sensor in the lock-in region, hence greater accuracy is achieved through missing fewer pulses.

The dither frequency has a random frequency component superimposed on it which randomises slightly the motion of the cavity. The result of this randomisation is that the motion has a randomised rate noise rather than a mean bias which would be produced by a sinusoidal motion of the cavity block [7]. This motion produces a random walk in angle which appears on the output of the sensor.

The use of mechanical dither causes an increase in size, weight and complexity. It is necessary to subtract the dither motion from the gyroscope's output and this may be accomplished either optically or electronically. Any difference between the actual and compensated output is termed dither spill over which leads to a scale-factor error.

Another technique that is currently being applied is called magnetic mirror biasing. This electro-optical technique uses a non-reciprocal magneto-optical effect (the transverse Kerr effect [8]). One of the highly reflective mirrors has a magnetic coating on its top surface. The magnetic coating, when saturated by an applied magnetic field, causes a difference in phase delay between the two counter-propagating laser beams, biasing the frequencies away from the lock-in zone. In order to prevent any drifts in bias voltage being interpreted as a rotation rate, it is necessary to switch between two bias points so any drifts average to zero. A potential disadvantage with magnetic mirrors is the introduction of higher cavity losses which may exclude it from high accuracy applications. However, it is a genuine solid-state sensor [9] which is smaller and less complex than the mechanically dithered ring laser gyroscope.

Multi-oscillator concepts have been demonstrated [10–12] where more than a single pair of beams propagate in the same cavity, usually four beams in a square configuration. Independent lasing of left and right polarised modes are propagated in each direction in the cavity, giving a total of four modes. Avoiding the phenomenon of lock-in still applies, so it is necessary to bias the modes away from this zone. The reciprocal splitting between the right-hand and left-hand circularly polarised modes can be several hundred megahertz, achieved by using a quartz retarder plate, or a non-planar cavity configuration. The real difficulty is to achieve adequate biasing of the direction dependent (non-reciprocal) modes, that is, the clockwise and anti-clockwise right-hand circularly polarised modes, and similarly with the opposite handed modes.

Three methods have shown promise: use of a Faraday rotation element in the laser cavity; a mirror with a magneto-optic coating that uses either the polar or transverse Kerr effect; application of a Zeeman field to the discharge to induce a frequency change. Sometimes the ring laser gyroscope that has a Faraday cell in its cavity is called the differential laser gyroscope or DILAG; the other name is the four-frequency gyroscope. One distinct advantage that this form of gyroscope has over the conventional ring laser gyroscope is an enhanced scale-factor; giving a sensitivity that is twice that of the equivalent sized conventional laser gyroscope.

5.1.3.4 Detailed description of the sensor

The more commonly used ring laser gyroscope configuration which uses three mirrors is illustrated in Figure 5.3. Successful configurations using four mirrors have also been produced.

The major components of the gyroscope, as shown in Figure 5.3, are:

1. The laser block—formed in a low expansion ceramic glass such as Zerodur or Cervit. Contained within it is the lasing medium which is usually a mixture of helium and two isotopes of neon to enable the two modes to propagate without competition.
2. The optical components—usually just the mirrors and photo-detectors, but an optical biasing element may also be included in the laser cavity. There are two types of mirror; the partially reflecting (partially transmitting) 'output' mirrors, as mentioned above, and the mirror with a very high reflection coefficient. All of the mirrors are multi-layer dielectric stacks of alternate layers of materials with a different refractive index, deposited on extremely high quality polished substrates to give very low back scatter. One of the mirrors is attached to a piezoelectric device so that it can be moved in and out to maintain a constant path length (at the resonant condition) as the temperature changes. The other mirrors are

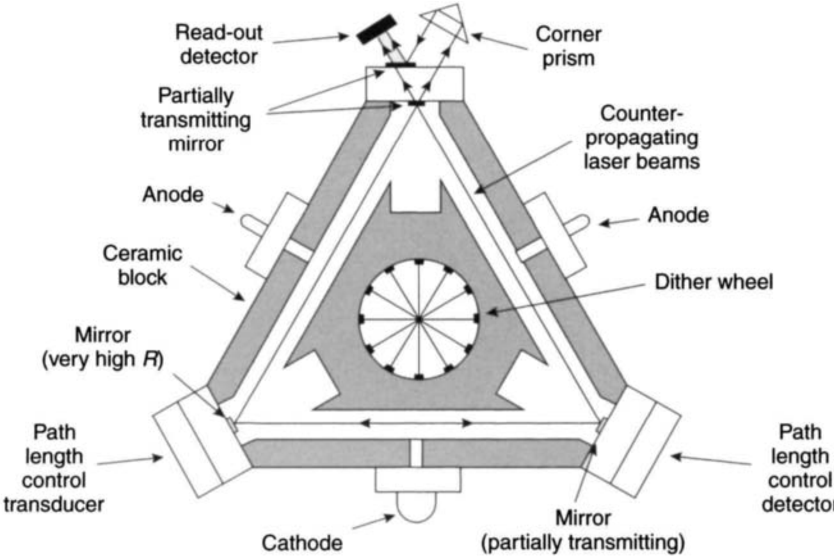


Figure 5.3 Schematic diagram of a ring laser gyroscope

firmly bonded directly to the laser block. A variety of techniques are used including optical contacting, using soft metal seals such as gold and indium, and an alternative bonding technique known as frit sealing.

3. The non-optical components—the usual configuration is to have one cathode and two anodes which produce a discharge when a high voltage is applied to these electrodes. This discharge then provides the source of excitation for the laser action. The usual laser wavelengths that are used are either the red line at 632.8 nm or the 1.152 μm line in the infrared part of the electromagnetic spectrum.
4. The biasing mechanism required to overcome the lock-in phenomenon described in detail above. A bias can be applied by various techniques such as mechanical dither, magnetic mirror or the use of optical elements within the laser cavity.

A photograph of a mechanically dithered ring laser gyroscope is shown in Figure 5.4.

The primary disadvantage of this technology is the precision engineering that is required to make and polish the faces of the laser block and the high technology required to produce the mirrors. This tends to make the cost of the sensor quite high, although techniques for reducing this are being sought. A further anticipated problem is the potential for helium to leak out of the cavity through one of the many seals. Radio frequency pumping of the laser cavity has been demonstrated and is a method of reducing the number of components fitted into the block and hence reducing the number of orifices and seals through which this gas can leak.

Mirror quality assessment prior to assembly of the sensor is crucial to the performance and yield achieved in production of these devices. It is usual to evaluate

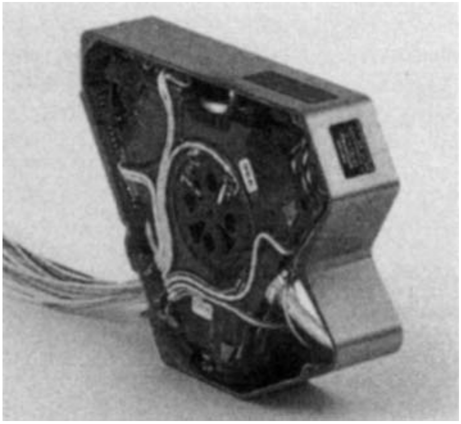


Figure 5.4 Mechanically dithered ring laser gyroscope

scatter, loss, surface quality and flatness. The two mirror parameters that are most closely related to sensor performance are the scatter and loss. Deterioration of the mirrors is minimised by operating the gyroscope at the lowest possible internal laser intensity consistent with reliable performance.

More recent developments use an optical arrangement that has four independent beams in the cavity. Suitable comparison between the frequencies of the different beams enables the lock-in phenomenon to be eliminated without the use of mechanical motion (dither). The Northrop-Grumman (formerly Litton Industries) optically biased, four-beam ring laser gyroscope, termed the Zero-Lock™ Laser Gyroscope, is shown in Figure 5.5.

5.1.3.5 Sources of error

There are three types of error which are characteristic of a ring laser gyroscope:

1. the lock-in phenomenon considered in detail above;
2. null shift, where the input/output characteristic does not pass through the origin so that the sensor records some counts from the detector even when stationary;
3. scale-factor changes resulting from mode pulling effects.

A null shift error arises when one of the laser beams experiences some difference in its optical path when compared with the other laser beam. Hence, the use of a split discharge and the balancing of the discharge currents in the two discharges in order to make the laser cavity as isotropic or reciprocal as possible. Similarly, the sensor is usually shielded from stray magnetic fields in order to minimise any unwanted magneto-optic effects, particularly in the mirrors.

Mode pulling effects, considered by Lamb [13], give rise to dispersion effects, normal or anomalous. Any changes in the dispersive effects of the laser medium can

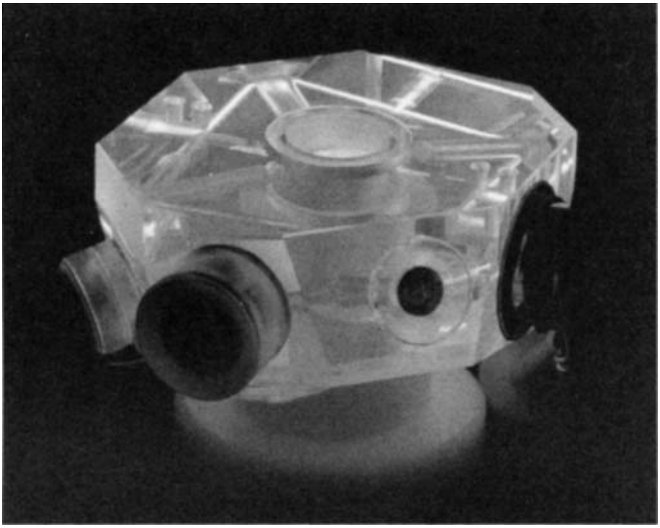


Figure 5.5 *Zero-Lock™ Laser Gyroscope (published courtesy of Northrop Grumman Corporation, Litton Systems)*

give rise to instabilities and continuous changes to the scale-factor. All of these errors are considered in detail by Aronowitz [6].

The stability of the sensing axis is also a key parameter which influences system performance. This is defined by the plane containing the laser beams which can move owing to disturbances in the laser block and movements of the beam induced by non-parallel motion of the cavity path length control mirror.

The output of a ring laser gyroscope ($\tilde{\omega}_x$) may be expressed mathematically in terms of the input rate ω_x and the rates about the axes which lie in the lasing plane (ω_y and ω_z) as:

$$\tilde{\omega}_x = (1 + S_x)\omega_x + M_y\omega_y + M_z\omega_z + B_x + n_x \tag{5.16}$$

where S_x is the scale-factor error, M_y, M_z are the misalignments of the gyroscope lasing plane with respect to the nominal input axis, B_x is the fixed bias and n_x is the random bias error.

The random bias term includes the random walk error referred to earlier which gives rise to a root-mean-square magnitude of angular output which grows with the square root of time. Whilst present to some extent in mechanical gyroscopes, the effect is generally an order of magnitude larger in optical sensors. In a mechanically dithered ring laser gyroscope, this error is largely caused by the random phase angle error introduced as the input rate passes through the lock-in region. An additional noise term gives rise to a bounded error and is the result of scale-factor errors in the mechanism used to eliminate lock-in.

5.1.3.6 Typical performance characteristics

With careful design, this form of gyroscope does not exhibit any significant acceleration or vibration sensitivity. The typical range of performance that can be achieved from these devices is as follows:

g-Independent drift (bias)	<0.001–10°/h
g-Sensitive bias	Usually insignificant for most applications
g^2-Sensitive bias	Usually insignificant for most applications
Scale-factor errors	Few parts per million to 0.01% (of maximum rotation rate)
Bandwidth	>200 Hz (can be made very large)
Maximum input rate	Several thousand degrees per second
Random walk	0.001–0.01°/h

Hence, the key parameters are the bias repeatability, random noise, scale-factor repeatability and sensing axis stability.

5.1.4 Three-axis ring laser gyroscope configuration

Various schemes have been proposed and implemented to produce a single sensor with three sensitive axes using ring laser technology. Such devices are commonly called triads. These configurations are generally based on the use of three mutually orthogonal square laser cavities within a single cubic block. This arrangement enables each mirror to be shared by two of the laser cavities so only six mirrors are required for this device [14]. Similarly, the cathode is shared between discharges. The use of mechanical dither, applied about a body diagonal of the laser block, enables a bias to be applied simultaneously to each of the individual sensors within the monolith, and hence alleviate the lock-in problem for each of the axes.

Use of such a configuration can be very attractive for a number of applications as it provides great stability between the axes. The cost and complexity can also be reduced compared with the use of three independent sensors by using one dither mechanism, one discharge circuit and reducing the number of mirrors required through sharing.

The major disadvantage of such a system is the care needed and difficulty in machining the laser block to the necessary accuracy as well as avoiding damage during production, that is, achieving a high yield. Additionally, a single fault could mean that all three axes of angular motion information is lost.

A schematic diagram of a triad is shown in Figure 5.6.

5.1.5 Fibre optic gyroscope

5.1.5.1 Introductory remarks

Work at the US Naval Research Laboratories in the late 1960s suggested that multiple circulations of a Sagnac interferometer may give sufficient sensitivity to enable angular rotation to be detected and measured. By the mid-1970s, research progressed

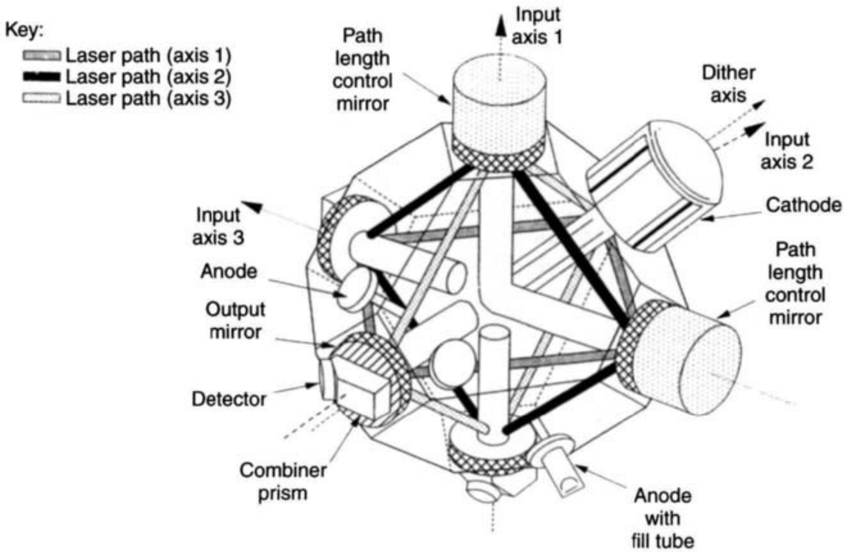


Figure 5.6 Schematic diagram of a triad

significantly on the use of passive interferometric techniques to sense angular motion, by applying optical fibre technology to form the light path [5]. This approach was seen as offering a far cheaper alternative to the ring laser technique, as the need to machine and polish surfaces to fractions of an optical wavelength would not be required. However, it was recognised that this approach was thought unlikely to produce a sensor with true high performance inertial performance characteristics, that is, drift values in the region of 0.01°/h or better. Application of modern technology and technique has enabled this goal to be achieved.

In contrast with the ring laser technology, the fibre optic gyroscope senses angular motion by detecting the phase difference between the two beams passing round the light path in opposite directions. The gyroscope can be constructed as a genuine solid-state sensor, even in a closed loop mode, by the use of integrated optical components (chips). Use of this technology means that this type of inertial instrument can be very compact. However, extreme care and good design is required with the necessary fibre connections to avoid failure in harsh environments. Currently this is the subject of various research projects in many parts of the world [15].

These sensors have found many applications, particularly in the robotics and automobile industries. Aerospace applications are developing, especially for stabilisation and inertial navigation.

5.1.5.2 Principle of operation

Operation of the fibre optic gyroscope is dependent on the formation of a Sagnac interferometer [16]. In its simplest form, light from a broad band source is split into two beams that propagate in opposite directions around an optical fibre coil.

These two beams are combined at a second beam splitter to form an interference pattern where the resultant intensity is observed using a photo-detector. When the interferometer is stationary, the path length of the two counter-rotating beams is identical so there is no phase difference resulting in maximum amplitude. However, when the fibre coil is rotated about an axis normal to the fibre coil, the light travelling in the same direction as the rotation travels slightly further than the light travelling in the opposing direction. The resulting phase difference results in a change in amplitude of the interference pattern formed when the two beams are recombined.

For a rotating fibre gyroscope with a single turn of fibre, the phase difference ($\Delta\Phi$) between the counter-propagating beams of light may be expressed in terms of the path difference (ΔL) generated when the device rotates as:

$$\Delta\Phi = 2\pi\frac{\Delta L}{\lambda} \tag{5.17}$$

Substituting for ΔL from eqn. (5.6) gives:

$$\Delta\Phi = \frac{8\pi A\Omega}{c\lambda} \tag{5.18}$$

where A is the area enclosed by the fibre coil, Ω is the applied rotation rate and c is the velocity of light.

For a coil of N turns, this becomes:

$$\Delta\Phi = \frac{8\pi AN\Omega}{c\lambda} \tag{5.19}$$

This may be expressed in terms of the length of the fibre ($L = 2\pi RN$) as:

$$\Delta\Phi = \frac{4\pi RL\Omega}{c\lambda} \tag{5.20}$$

Consider a coil of radius 40 mm containing a 100 m length of fibre. If the optical wavelength is 850 nm, the phase differences which occur for rotation rates of (a) 15°/h and (b) 500°/s are as follows:

(a) $\Delta\Phi = 0.0008°$

(b) $\Delta\Phi = 98.6°$

Clearly, if a sensor is going to be capable of detecting Earth's rate or comparable rotations, a high level of dimensional stability will be necessary. Hence, light travelling one way around the fibre coil must travel exactly the same path as the light which travels in the opposite direction, that is, reciprocity must be maintained.

Comparing this equation with eqn. 5.11 for the ring laser gyroscope, the difference in sensitivity between the two sensors is obvious owing to the occurrence of the velocity of light in the denominator of the above equation. Hence, it is necessary to measure minute phase shifts to achieve high performance, which is a non-trivial task, but application of modern techniques enables this measurement accuracy to be achieved.

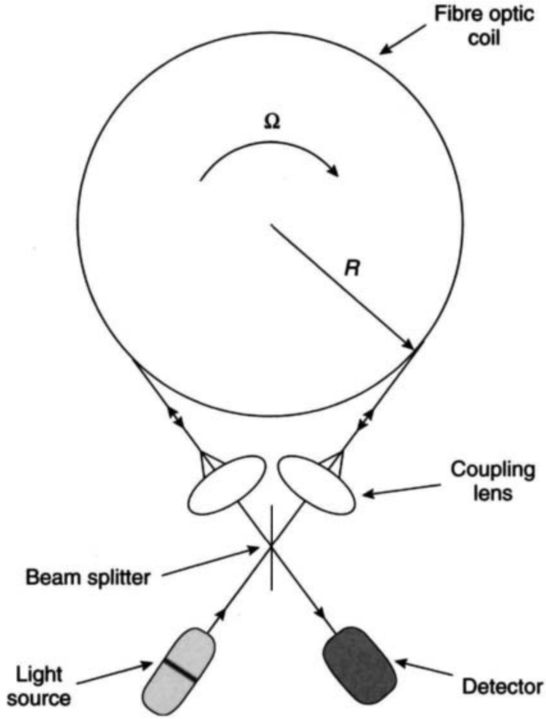


Figure 5.7 Open-loop fibre optic gyroscope

5.1.5.3 Detailed description of the sensor

The fundamental optical components of a fibre optical gyroscope, as illustrated schematically in Figure 5.7, are:

1. A light source, usually a broad band source with a coherence length chosen to minimise the scattering effects within the fibre.
2. Couplers to link energy into and out of the fibre. It is usual to use 3 dB couplers so they act as beam splitters.
3. The fibre coil, the angular motion sensing element. As a small single coil is unlikely to provide sufficient sensitivity, multiple turns are used. Depending on the desired sensitivity, high birefringence mono-mode or polarisation maintaining fibre may be used.
4. The detector, a photo-diode used to detect the changes in the fringe pattern.

The non-optical components include the former on which the fibre coil is wound and the electronic components.

The fibre optic gyroscope can be operated in either an open-loop mode or a closed loop mode [16–18]. When it is used in the simple open-loop configuration, it is particularly sensitive to any non-reciprocal effects, consequently reducing the sensitivity of the device.

Open-loop operation

A scheme was devised that ensured that both of the returning waves had propagated along the identical path, but in opposite directions. This was achieved by projecting polarised light into the interferometer through a single mode waveguide, such as a mono-mode optical fibre, and observing the returning interference wave which had been filtered by the same waveguide prior to detection. This arrangement is known as the reciprocal or minimum configuration gyroscope, and is shown schematically in Figure 5.8.

The returning light beams from the fibre coil are combined at the second beam splitter and emerge from the so-called reciprocal port. These two beams are exactly

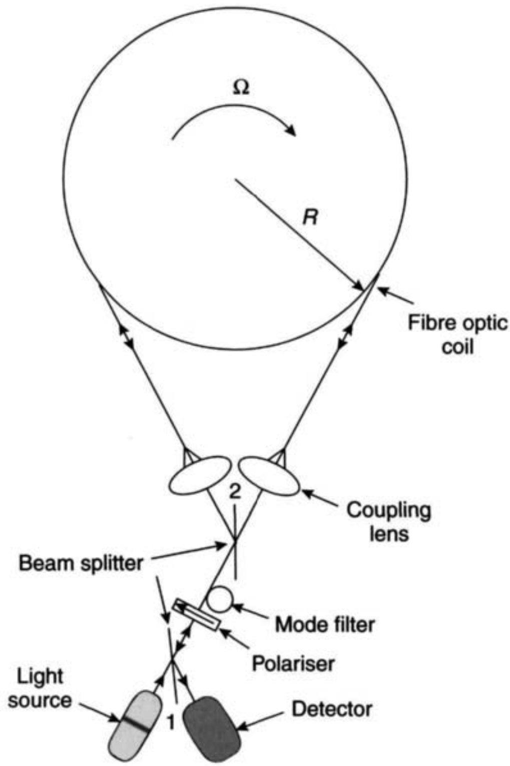


Figure 5.8 Reciprocal configuration fibre gyroscope and detector response

in phase when the fibre coil is at rest, but the resultant intensity varies sinusoidally with the rate of angular rotation of the coil. The major disadvantage of this form of fibre gyroscope is the lack of sensitivity at small applied input rates, owing to the co-sinusoidal shape of the fringe pattern, as shown in Figure 5.8.

It is possible to modify the fringe pattern to enhance the sensitivity at low rotation rates by incorporating a phase modulator at one end of the fibre coil. This modulator acts like a delay line. It is operated asymmetrically to give a phase dither of $\pm\pi/2$, which appears at the detector at twice the modulation frequency. Consequently, the gyroscope (detector) output is now biased to give its greatest sensitivity at and around small rotation rates. However, the response is still sinusoidal. This is illustrated in Figure 5.9 which also shows a schematic diagram of a phase biased fibre gyroscope.

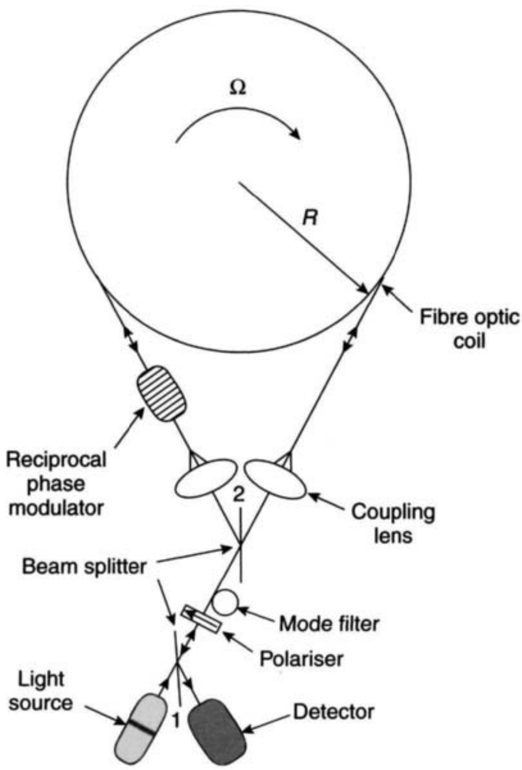


Figure 5.9 Phase biased fibre gyroscope and detector response

The phase modulator can be made by winding a few turns of optical fibre round a piezoelectric cylinder. A square wave signal may be applied to this cylinder to make it change shape and consequently to modulate the optical path length of the fibre coil.

Closed loop operation

There are many applications that require good accuracy over a wide angular rate range, possibly up to hundreds of degrees per second, and not merely at or close to 'zero rate'. It is generally desirable that the scale-factor linking the perceived angular motion to the actual motion should have good stability, be linear and be independent of the returning optical power. This can be achieved using a closed loop signal processing approach. Two techniques, or architectures, have been demonstrated, namely phase nulling and frequency nulling.

In the case of phase nulling, a second phase modulator is added to the 'other end' of the fibre coil, as shown in Figure 5.10. It is operated at twice the frequency of the dither (biasing) modulator and is used to 'back-off' or null the effects of the Sagnac induced phase shifts caused by the angular motion of the fibre coil. The open-loop signal is used as an error signal to generate an additional phase difference ($\Delta\phi_n$) that has an opposite sign to the rotation induced phase difference. Consequently, the total phase difference is arranged to be at or very close to the 'zero' value, so that the system is operated about the point of greatest sensitivity. The value of the additional feedback ($\Delta\phi_n$) is used as a measurement of angular rate. It has a linear response with good stability, since it is independent of the power of the returning optical signal and the gain of the detection system. However, the accuracy of the scale-factor does depend on the stability of the source wavelength and the geometric stability of the sensing coil.

An alternative technique for achieving closed loop operation is through the use of a frequency shift generated by an acousto-optical modulator, or Bragg cell, placed at one end of the sensor coil. This frequency shift is used to produce a differential phase shift to null that caused by the Sagnac effect [15]. By varying the voltage applied to the Bragg cell, the frequency shift it induces can be varied. Hence, the voltage that needs to be applied to the Bragg cell to null the detector's output is directly proportional to the applied angular motion.

The frequency shift given to the light by the Bragg cell is chosen so that the sensor is operated in the region where it is most sensitive to low rotation rates, as described above. This frequency shift produced by the Bragg cell is dithered about the centre frequency using a square wave modulator and the intensities of the light beams incident on the detector are monitored. When the sensor coil is rotated about its input axis, a small phase shift is introduced between the two beams giving rise to a mismatch between the intensities of the two beams on the detector. Consequently, the output signal from the detector will be modulated at the dither frequency. A phase sensitive detection system is used to deduce the amount that the centre frequency of the Bragg cell needs to be altered in order to return the intensities to their original matched state, thereby nulling the sensor. This change in the voltage applied to the Bragg cell is directly proportional to the applied angular motion.

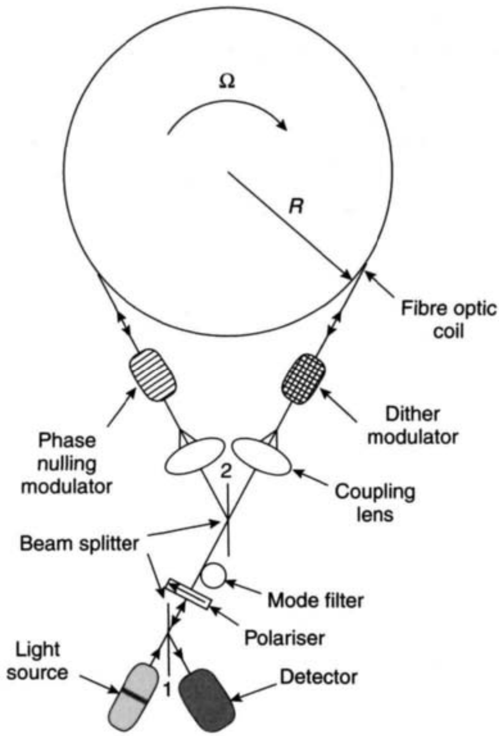


Figure 5.10 Closed loop (phase nulled) fibre gyroscope and detector response

The principal drawback of this architecture is the generation of a suitable bandwidth of frequencies in the modulator. This can be achieved by using two acousto-optical modulators at opposite ends of the sensor coil and dithering their frequencies about a centre frequency. An alternative approach is to use two modulators in opposition at one end of the fibre coil. With both arrangements, great care is required to achieve satisfactory mechanical stability of the whole assembly.

One technique that is currently used is the so-called phase ramp, serrodyne modulation [16], which relies on the fact that a frequency can be considered to be a time derivative of phase. In practice, a sawtooth waveform is used to modulate the applied phase shift, with a very fast 'flyback' at the reset positions. An alternative method that alleviates the 'flyback' problem is the digital phase ramp. In this case, 'phase steps' are generated with a duration equal to the group delay difference in time between the long and short paths that connect the phase modulator and the beam splitter. These 'phase steps' and the resets can be synchronised with a square-wave biasing modulation. The use of digital logic enables this technique to be implemented easily.

One of the current developments of the fibre optic gyroscope is the demonstration of the so-called integrated fibre optic gyroscope. In this device, all the bulk optical, or fibre, components are replaced with components fused into a lithium niobate substrate [16]; it is used to produce the beam splitter or couplers, optical waveguides and the necessary modulation to the light required to measure the rotation rate accurately. Fibre 'leads' are used to connect the source and detector to this so-called integrated optics 'chip'. This form of gyroscope has the potential to be compact, rugged and have a long shelf-life whilst retaining the advantages of optical sensors listed earlier in Section 5.1. Currently these sensors are about 70–80 mm in diameter; a size which is a compromise between producing a compact sensor and avoiding excessive biases induced by the strain in the fibre when bent into a small radius of curvature. Photographs of a commercially available fibre optic inertial measurement unit are shown in Figure 5.11.

As perceived, the use of a reciprocal path in optical sensors like the fibre optic gyroscope should be free from errors associated with the environment, such as temperature, acceleration and vibration. However, regrettably these devices do exhibit some sensitivity to these effects. Fortunately, through careful design, particularly the winding of the sensor coil, these sensitivities can be minimised. These effects are considered below.

5.1.5.4 Sources of error

Changes in ambient temperature can cause a bias or drift to be observed because of a multitude of effects within the sensor, temperature gradients within the sensor being a particular problem. As the ambient temperature changes, the source wavelength changes and the sensitivity of the sensor is inversely proportional to the source wavelength. Temperature changes result in variation of the refractive index of the optical fibre leading to changes in the modulation. If possible, the expansion coefficient of the fibre and the coil former should be well matched, or else differential stresses are induced by thermal expansion which result in measurement errors. Thermal changes also alter the size of the coil resulting in changes in the scale-factor of the gyroscope.

A bias occurs when there is a time-dependent thermal gradient along the optical fibre as a result of a temperature gradient across the coil. This results in a non-reciprocity occurring when corresponding wave fronts of the counter-rotating beams cross the same region at different times. This is known as the Shupe effect [19]. Anti-Shupe windings have been devised so that parts of the optical fibre that are equal distances from the centre of the coil are adjacent.

When an acceleration is applied to a coil, it can result in the distortion of the coil producing a change in the scale-factor of the gyroscope. Distortions also change the birefringence of the fibre and hence, the bias of the sensor. Additionally, distortions can lead to changes in the direction of the sensitive axis and, in the case of a three-axis configuration, changes in the relative orientation or alignment of the three input axes.

(a)

(b)

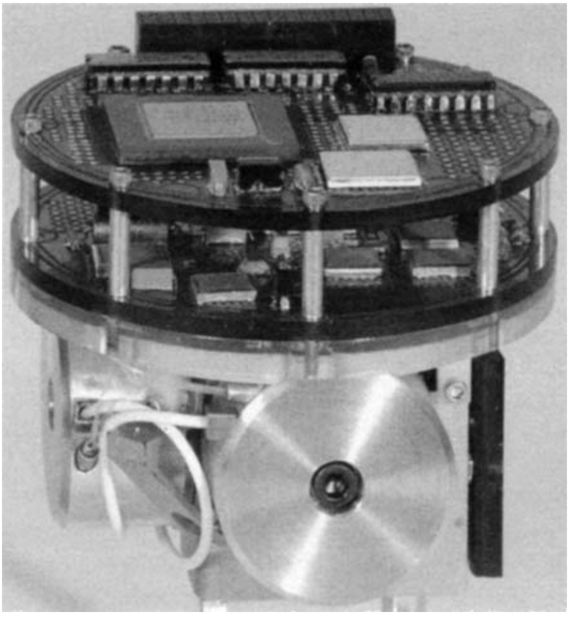


Figure 5.11 Inertial measurement unit containing fibre optic gyroscopes (published courtesy of Northrop Grumman Corporation, Litton Systems)

Application of vibratory motion to a coil of fibre, or length of fibre, can lead to a distortion of the coil and the fibre, depending on the amplitude of the input motion. As discussed earlier, this leads to errors in the angular motion measurements made by the sensor.

The presence of stray magnetic fields also can have an adverse effect owing to interaction with the non-optical components. Magnetic fields can also produce changes in the state of polarisation of the light in the optical fibre through the Faraday effect. These sensitivities lead to a bias in the output signal from the device. The use of magnetic shielding can minimise this effect.

The bias and drift in the output signal is a consequence mainly of birefringence in the optical fibre and propagation of cladding modes, as well as polarisation modulation of the optical signals. The problem is essentially one of many modes existing within the fibre, each with a different phase and with a lack of coherence, so fading occurs. One method of overcoming spurious coherent effects, including scattering within the fibre, is to use a low coherence source, i.e. one with a short coherence length. A superluminescent diode fulfils this criterion. Use of this source also minimises the bias generated by the Kerr electro-optic effect, caused by changes in the refractive index of the optical medium through variations in the power of the two counter-propagating beams.

5.1.5.5 *Typical performance characteristics*

Typical performance parameters for fibre optic gyroscopes are given below:

g-Independent bias	0.5–50°/h
g-Sensitive bias	~1°/h/g
g^2-Sensitive bias	~0.1°/h/g^2
(g-Dependent biases can be made negligible with good design but often show some sensitivity)	
Scale-factor errors	0.05–0.5%
Bandwidth	>100 Hz
Maximum input rate	>1000°/s

Many techniques have been developed to reduce the sensitivity of these sensors to the environment in which they operate and it is anticipated that significant progress will be demonstrated in the near future. It is worth noting that these 'problems' are far less severe than those which occurred with the mechanical gyroscopes 30 years earlier!

5.1.5.6 *Recent developments in fibre optic gyroscope technology*

Fibre optical gyroscope technology has developed significantly over the last 5–10 years. The closed loop device interferometric fibre optical gyroscope (IFOG) has seen very substantial increases in performance owing to:

- the developments in the super luminescent diode technology;
- enhanced optical fibres with lower optical loss, lower scatter and greater uniformity;

- the perfection of the functions of the integrated circuit chip, such as the polarisation of the light, the splitting of the beam into the clockwise and counter-clockwise beams, the recombination and control of the frequency shifting process;
- the development of microprocessor technology that can be combined within the sensor to give real-time accurate compensation of systematic errors.

Modern technology enables each sensor to be calibrated and appropriate compensation techniques applied, particularly for the effects of changes in temperature. Moreover, it allows the same architecture to be used in different performance sensors, by reducing the length of optical fibre needed for the lower performance devices. However, the modulation frequency still has to be tracked to the actual length of fibre to give the optimum performance for the chosen fibre length.

The measurement accuracy of these IFOGs is now approaching, if not comparable with, that of a standard inertial-quality ring laser gyroscope. The IFOG devices have yet to supersede the ring laser gyroscope in the high performance applications owing to the industrial investment in this technology base. However, as the cost of the IFOG technology decreases they are very likely to replace ring laser gyroscopes. A high-performance IFOG can have the following performance characteristics.

Parameter	Value
Bias stability	$<0.0003°/\text{h}$
Random walk	$<0.00008°/\sqrt{\text{h}}$
Scale-factor error	<0.5 ppm

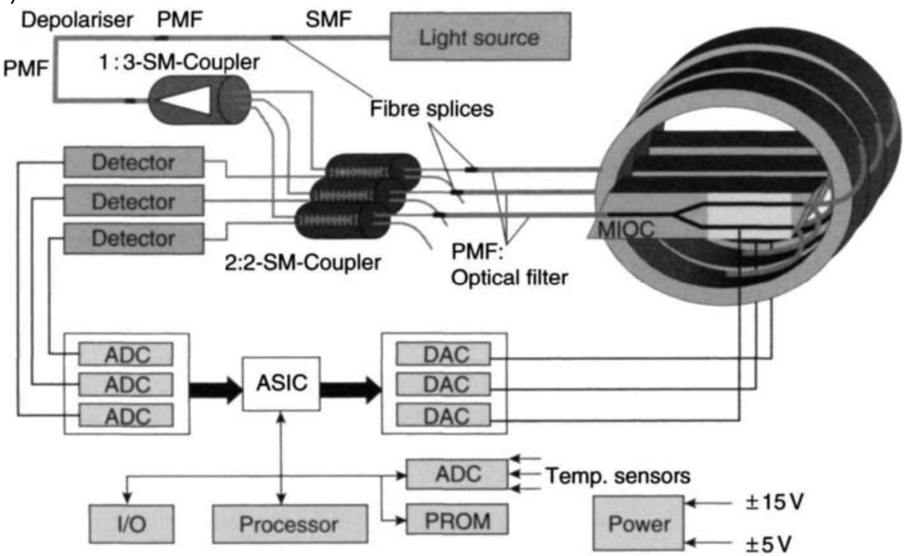
IFOG technology has been used in many lower-grade applications. Examples include: unmanned air vehicles, unmanned underwater vehicles, many types of stabilisation, gyrocompasses, and attitude and heading reference systems.

The major thrust is cost and size reduction. A typical example is the development of a fibre optical gyroscope triad system, a system being produced by the Litef company in Germany. In this system the cost of the super luminescent diode was identified as a major cost driver in any FOG-based system. The solution was to use a single super-luminescent diode and share the light with the three fibre coils via their integrated optical chips. This class of optical device is reported to have a bias stability in the 0.05°/h class. Changes to the coil design enables lower-grade performance to be achieved, but still maintaining a very high-quality linear scale-factor. A schematic of this arrangement is shown in Figure 5.12.

5.1.6 Photonic crystal optical fibre gyroscope

New optical fibre technology [20] is being developed that gives superior light-guiding properties compared with traditional step-index fibres. These new optical fibres have a periodic array of holes in the structure that provide very high-quality light-guiding

(a)



(b)

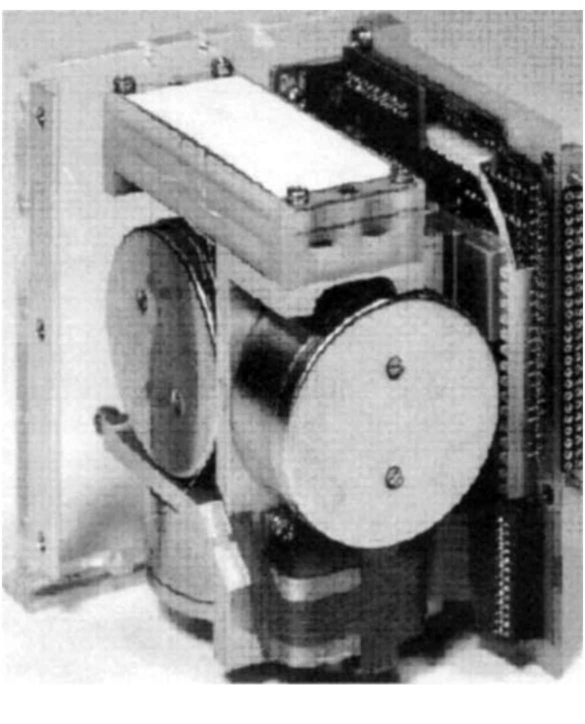


Figure 5.12 (a) Fibre optical gyroscope triad structure. (b) Sensor block (published courtesy of Litef GmbH)

properties with very low optical losses. In fact they are sometimes known as holey fibres and come in two forms depending on the construction of the core:

- photonic crystal fibres have a solid core, to transmit the light, that is surrounded by an array of holes that give a reduced refractive index to the surrounding medium;
- photonic band gap devices with a void or defect in the centre of the core for the transmission of light, so the light passes along a hollow core. The array of holes creates a band gap analogue to a semiconductor allowing the light to propagate in only certain parts of the structure, trapping it in others.

These classes of fibre provide very tight mode confinement of the propagating light, and single mode propagation is possible over many wavelengths. Additionally, the polarisation maintaining versions of these fibres have demonstrated ten times the birefringence of the conventional fibres.

The tight mode confinement results in much smaller bend losses so tighter coils can be produced leading to much smaller packages. Additionally, the smaller cladding structure also allows small devices to be made without impeding performance.

It is possible to embody dispersion compensation into these fibres to reduce the effects of spectral distortion of the propagating light on the performance of the sensor. Additionally, the micro-structured fibres could be used with light having a wavelength in the 1–2 μm waveband.

Figure 5.13 shows two types of micro-structured optical fibre.

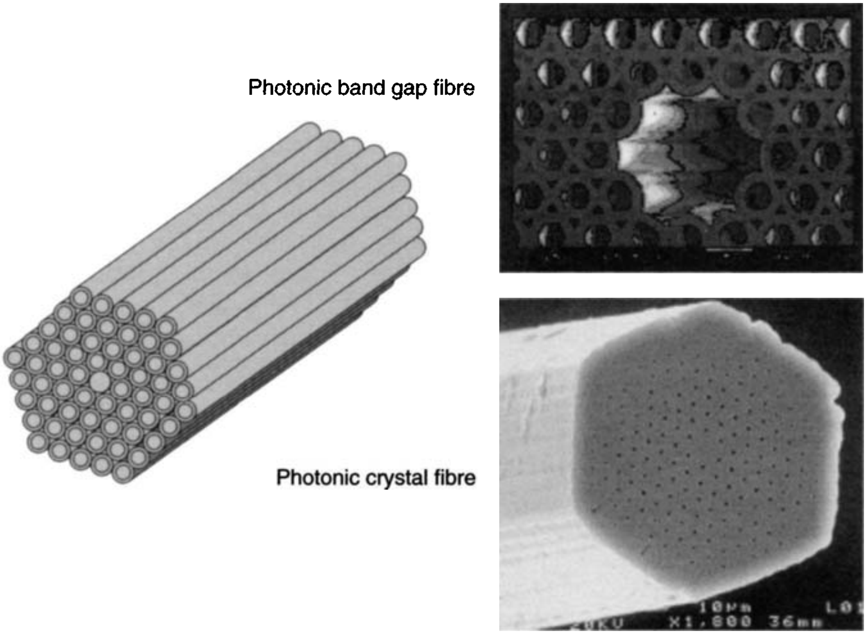


Figure 5.13 Micro-structured fibres

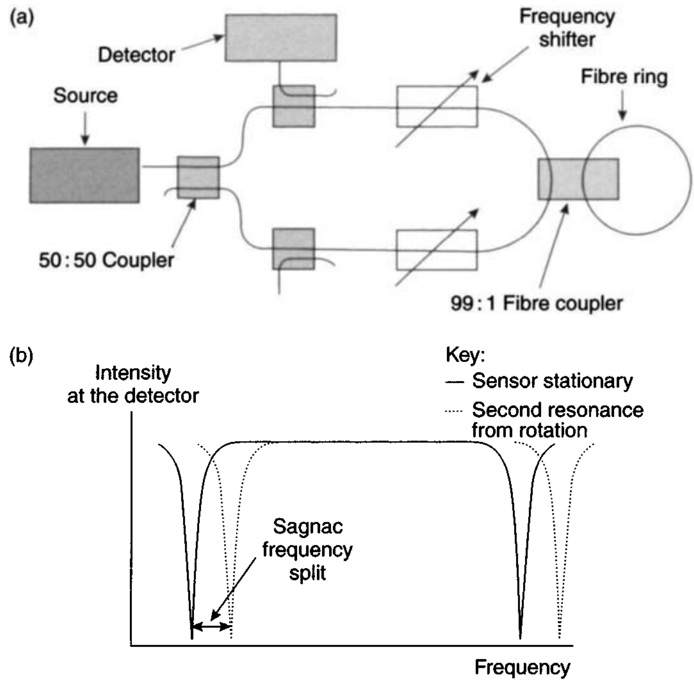


Figure 5.14 *Fibre optic ring resonator gyroscope (a) and intensity waveform (b)*

5.1.7 Fibre optic ring resonator gyroscope

This is yet another implementation of the Sagnac effect and could be considered to be a development of the fibre optic gyroscope. Work to develop this concept started at various institutions in the early 1980s, much of the pioneering work being led by Dr Ezikiel at the Massachusetts Institute of Technology.

This type of gyroscope uses a recirculating ring resonant cavity to enhance the phase differences induced by the Sagnac effect when the sensor is rotated. A ring cavity is formed by joining the ends of a short optical fibre cable, typically 10 m or less, to a coupler, as shown in Figure 5.14a. The light enters and leaves the ring cavity through this coupler.

The principle of operation of the ring cavity is very similar to that of a Fabry–Perot interferometer [16], but with multiple interference between the recirculating waves and the light being introduced to the cavity. Resonance can be achieved in the ring either by stretching the fibre or by sweeping the frequency of the light, thus resulting in constructive interference occurring in the ring and hence maximum light intensity.

At resonance, there is a dip in the light intensity reflected at the output port resulting from the majority of the light entering the fibre ring and then being lost by scattering after many recirculations in the ring cavity. Figure 5.14b shows the form of the intensity waveform at the detector. The width of the resonance is set by the finesse of the resonator [21]. This parameter is inversely proportional to the coupling ratio into the ring. Hence, it is necessary to have a high coupling ratio. The quality of the cavity, and its sensitivity, is defined by the finesse, which is the ratio of the free spectral range to the linewidth of the resonance. The resonant condition is observed by detecting the energy reflected by the coupler linking the fibre ring to the source and detector.

When the sensor is stationary, the resonant frequencies of the two counter-propagating beams are identical. When the ring is rotated about its sensitive axis, the resonant frequencies of the two counter-propagating beams differ. This results in a shift in the positions of the resonances and hence, in the light intensity from the output port.

Equation (5.19), derived earlier, for the fibre optic gyroscope gives the phase difference for the two beams. Because the two counter-propagating beams experience different loop paths, there is a different resonance frequency (ν_d) generated in each direction. It is given in terms of the radius of the coil by substitution for A ($=\pi R^2$) and L ($=2\pi R$) in eqn. (5.11). Hence:

$$\nu_d = \frac{2R\Omega}{\lambda} \tag{5.21}$$

where R is the radius of the coil, Ω is the applied rate and λ is the wavelength.

Clearly, the number of turns of fibre does not influence its sensitivity, as this is dependent on the radius of the loop for a given wavelength and rotation rate. Hence, given practical considerations, the length of optical fibre required is very much less, typically of the order of 10 m.

This sensor is used in a feedback mode so the frequency of the two counter-propagating beams is shifted when the sensor is rotated, thus keeping the two beams at resonance simultaneously even under rotation. Sinusoidal phase modulation with frequency modulation can be applied to the two counter-propagating beams. The difference between the two modulations required to maintain resonance in the two beams is proportional to the applied rotation rate.

The fundamental requirement for the light energy used in this sensor is that it has a narrow bandwidth and a high coherence. Hence, a light source is needed that is very stable in order to maintain the narrow width resonance in the ring. Currently, the lasers that fulfil this requirement are expensive, but with the development of quantum well lasers the price should reduce. Careful design is required to avoid incoherent back-scattering from one beam to the other and the consequent onset of the familiar 'lock-in' problem. It is usual to control the polarisation of the light before it enters the ring to avoid intensity fading.

As in the case of the fibre optic gyroscope, the bulk optical components can be replaced with integrated optical materials using guided waves. Hence this, together with the very short length of fibre, typically 10 m or less, can lead to a very compact sensor.

Currently, this sensor is being developed by a number of companies but definite performance and error data are not available. However, it is expected to have a similar performance to the fibre gyroscope; data for that sensor are given in Section 5.1.5.5. Generally, it is considered to be more sensitive than the fibre gyroscope, possibly by a factor of 3 [22].

5.1.7.1 Ring resonator rotation rate sensors – non-linear mode

Currently the measurement of rotation rate by the exploitation of non-linear effects, induced in the energy in the ring resonator, has been investigated. These non-linear effects occur when there is only a small loss, of the order of 5 per cent, in the ring, leading to about a 20-fold increase in power. The non-linear interactions are usually divided into two groups, intensity dependent refractive index effects and scattering phenomena. In the case of the fibre optic gyroscope, these non-linear effects are considered detrimental as they degrade performance.

The non-linear refractive index effect makes use of the Kerr effect [8]. The electric field of the optical energy propagating through a medium produces a refractive index change. Now, when a ring resonator, operating in a resonant condition, is rotated, the intensity in one direction decreases whilst the intensity in the other direction decreases. Additionally, the refractive index in each direction also changes, amplifying the intensity change. This amplification can be varied by changing both the parameters of the resonant ring and the Kerr material, which, in turn, improves the sensitivity of the resonator.

The propagation of a high power optical beam through a dense medium produces phonons; energy is transferred to these phonons resulting in a change in frequency of the beam. This results in a scattered optical wave with a modified frequency. The two major types of non-linear scattering are called Brillouin and Raman [23], and are threshold effects; Brillouin occurs at lower power levels. Brillouin scattering has a characteristic linewidth which requires a source with a coherence length shorter than the life time of a phonon. Consequently, a coherent source produces Brillouin scattering in preference to Raman.

It has been suggested [24] that a ring laser, exhibiting Brillouin scattering, pumped from both directions will produce a frequency difference between Brillouin scattered energy that is directly proportional to the rotation rate. This sensor should produce a signal that is similar to that produced by a ring laser gyroscope, that is, a rotation rate dependent frequency. However, there should not be any lock-in as the two scatter mechanisms should be independent.

A sensor has also been proposed based on the Raman scatter phenomena using high power pulses from a mode locked laser [25]. It appears that the major drawback will be the size of the sensor. Currently, there are no reports indicating that any of these sensors have been demonstrated.

5.1.8 Ring resonator gyroscope

This sensor is very similar to the fibre optic ring resonator, but the fibre ring is replaced with an optical waveguide which can be etched into a suitable substrate [26]. The principle of operation is very similar to that described for the fibre optic ring resonator. Typical rings are about 50 mm in diameter. Hence, when the problems associated with scattering and coupling can be overcome, the prospect of a gyroscope on a 'chip' can become a reality, along with all the advantages of optical sensors.

This type of sensor has been developed by Northrop in the United States [7] and is known as the micro-optic gyroscope (MOG). Rugged sensors with a diameter of about 25 mm have been produced with performance in the 1–100°/h category.

5.1.9 Integrated optical gyroscope

There have been developments in this highly desirable sensor, as it is a 'gyroscope on a chip'. The sensing element is an optical waveguide on a substrate with the light travelling in opposite directions. The relative position of the resonance within the ring is a measure of the applied optical rotation rate about an axis that is perpendicular to the ring. The fundamental operation of this device is described more fully in Section 5.1.7.

These integrated optical gyroscopes are created on wafers and combine micromachined electromechanical system processes and integrated optical fabrication processes. Speciality glasses are formed by highly specialised techniques such as flame hydrolysed deposition, radio frequency and reactive sputtering. The flame hydrolysed deposition allows the refractive index of the medium to be controlled so that the glass can be doped with rare earth laser ions, such as neodymium, ytterbium or erbium, creating lasers and laser amplifiers within the chip.

The definition of the waveguide is still quite a challenge, as vertical sidewalls with very low roughness are required to minimise losses. Clearly, the etching process is potentially the limiting process in the fabrication as there are likely to be various compositions of glass with varying dopant concentrations.

Currently, the performance goal is to meet applications requiring performance in the 0.1–1°/h regime. This class of sensor offers significant size and mass reduction, of the order of a factor of 20 compared with conventional fibre gyroscopes. Additionally, the power consumption is likely to be reduced by a factor of 5 or 6 along with a significantly lower cost owing to the reduced number of optical components.

5.2 Cold atom sensors

5.2.1 Introduction

This is an approach or technique for measuring inertial properties; such devices are also known as atom interferometer devices and owe much to the excellent work of Professor Chu of Stanford University. The technique is in the early stages of practical development and offers the prospect of a route to the most accurate accelerometers, gyroscopes, precision clocks and gravity gradiometers therefore performance enhancements of several orders of magnitude are predicted. If successful devices can be devised then, given precise knowledge of the gravity field, there is the prospect of a sub 10 m/h navigation capability without using global positioning system (GPS) or other external aiding techniques.

The sensor relies on the super cooling of an atom or molecule by techniques such as laser cooling and uses the de Broglie wavelength of an atom, which is about 3×10^4 smaller than the wavelength of visible light. The physical principle relies on