Theory and Applications of Optical Gyroscopes: Part I

The operating principles and the functions of active and passive ring laser gyros are examined first. Part II, appearing next month, will take up fiber-optic gyros.

The principle of operation of the *optical gyroscope*, first discussed by Sagnac [1], is conceptually very simple, although several significant engineering challenges had to be overcome before practical implementation was possible. In fact, it was not until the demonstration of the helium-neon laser at Bell Labs in 1960 that Sagnac's discovery took on any serious implications; the first operational *ring laser gyro* was developed by Warren Macek of Sperry Corp. just two years later [2]. Navigational quality ring laser gyroscopes were introduced into routine service in inertial navigation systems for the Boeing 757 and 767 in the early 1980s, and over half a million navigation systems have been installed in Japanese automobiles since 1987, many of which use *fiber-optic gyroscopes* [3]. Numerous technological improvements since Macek's first prototype have made the optical gyro one of the most promising sensors likely to significantly influence mobile robot navigation in the near future.

The basic device consists of two laser beams traveling in opposite directions (i.e., counterpropagating) around a closed-loop path. The constructive and destructive interference patterns formed by splitting off and mixing a portion of the two beams can be used to determine the rate and direction of rotation of the device itself. Schulz-DuBois [4] idealized the ring laser as a hollow doughnut-shaped mirror, wherein light follows a closed circular path. Assuming an ideal 100% reflective mirror surface, the optical energy inside the cavity is theoretically unaffected by any rotation of the mirror itself. The counterpropagating light beams reinforce each other to create a stationary standing wave of intensity peaks and nulls (see Figure 1), regardless of whether the gyro is rotating [2].

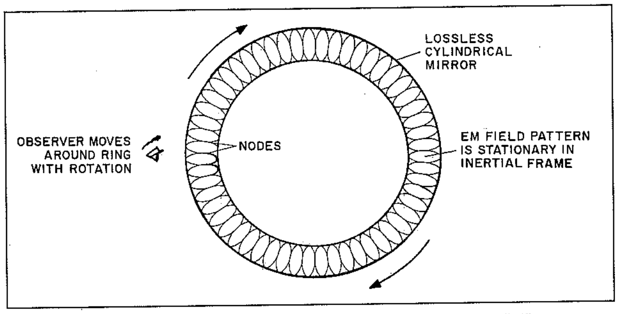

Figure 1. *Counterpropagating light beams create a standing wave in this idealized ring laser gyro. (Adapted from [2].)*

A simple visualization based on the Schulz-DuBois idealization will help explain the fundamental concept of operation before embarking on a more detailed treatment of the subject. The light and dark fringes of the nodes are somewhat analogous to the reflective stripes or slotted holes in the rotating disk of an incremental optical encoder and can theoretically be counted in similar fashion by an optical pickoff mounted on the cavity wall [5]. (In this analogy, however, the standing-wave "disk" is actually fixed in the inertial reference frame, while the normally stationary "detector" revolves around it.) With each full rotation of the mirrored doughnut, the detector would see a number of node peaks equal to twice the optical path length of the beams divided by the wavelength of the light. For a 632.8 nm HeNe wavelength in a typical 2.4-in.-dia. closed path, there are 300,000 wavelengths and hence 600,000 nodes, yielding over half a million counts per revolution [5].

Obviously, there is no practical way to implement this theoretical arrangement because there is no such thing as a perfect mirror. Furthermore, the introduction of light energy into the cavity (as well as the need to observe and count the nodes on the standing wave) would interfere with the mirror's performance, should such an ideal capability exist. However, numerous practical embodiments of optical rotation sensors have been developed for use as rate gyros in navigational applications. Five general configurations will be discussed:

- Active optical resonators
- Passive optical resonators
- Open-loop fiber-optic interferometers (analog)
- Closed-loop fiber-optic interferometers (digital)
- Fiber-optic resonators

Aronowitz [6], Menegozzi and Lamb [7], Chow et al. [8], Wilkinson [9], and Udd [10] provide in-depth discussions of the theory of the ring laser gyro and its fiber-optic derivatives. A comprehensive overview of the technologies and an extensive bibliography of preceding works are presented by Ezekiel and Arditty [11]. An excellent treatment of the salient features, advantages, and disadvan-

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tages of ring laser gyros vs. fiber-optic gyros is presented by Udd [10,12].

ACTIVE RING LASER GYROS

The *active optical resonator* configuration, more commonly known as the ring laser gyro, solves the problem of introducing light into the doughnut by filling the cavity itself with an active lasing medium, typically helium-neon. There are actually two beams generated by the laser that travel around the ring in opposite directions. If the gyro cavity is caused to physically rotate in the counterclockwise direction, then the counterclockwise-propagating beam will be forced to traverse a slightly longer path than it would under stationary conditions. Similarly, the clockwise-propagating beam will see its closed-loop path shortened by an identical amount. This phenomenon, known as the *Sagnac effect*, in essence changes the length of the resonant cavity.

The magnitude of this change is given by the equation [8]:

$$\Delta L = \frac{4\pi r^2 \Omega}{c} \qquad (1)$$

where:

ΔL = change in path length
r = radius of the circular beam path
Ω = angular velocity of rotation
c = speed of light.

Note that the change in path length is directly proportional to the rotation rate Ω of the cavity. To measure gyro rotation, some convenient means must therefore be established to quantify the associated change in the optical path length.

This requirement, to measure minute differences in optical path lengths, is where the invention of the laser in the early 1960s provided the needed technological breakthrough that allowed Sagnac's observations to be put to practical use. For lasing to occur in a resonant cavity, the roundtrip beam path must be precisely equal in length to an integral number of wavelengths at the resonant frequency. This means the wavelengths (and hence the frequencies) of the two counterpropagating beams must change, as only oscillations with wavelengths satisfying the resonance condition can be sustained in the cavity.

The frequency difference between the two beams is given by [8]:

$$\Delta f = \frac{2 f r \Omega}{c} = \frac{2 r \Omega}{\lambda} \qquad (2)$$

where:

Δf = frequency difference
λ = wavelength

In practice, a doughnut-shaped ring cavity would be hard to realize. For an arbitrary cavity geometry, the expression becomes [8]:

$$\Delta f = \frac{4 A \Omega}{P \lambda} \qquad (3)$$

where:

A = area enclosed by the closed-loop beam path
P = perimeter of the beam path

For single-axis gyros, the ring is generally formed by aligning three highly reflective mirrors to create a closed-loop triangular path (see Figure 2, page 57). (Some systems, such as Macek's early

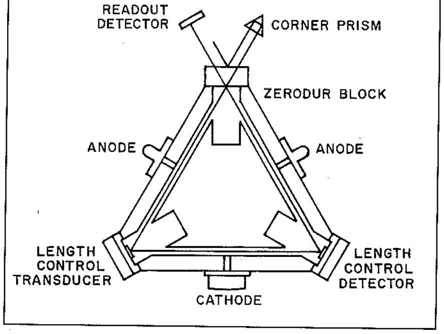

Figure 2. *A typical three-mirror configuration of the single-axis ring laser gyro incorporates dual anodes to cancel the biasing effects of induced Langmuir flow in the laser medium. (Adapted from [12].)*

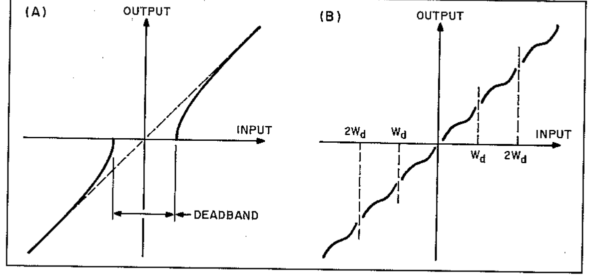

Figure 3. *Frequency lock-in due to a small amount of backscatter from the mirror surfaces results in a zero-output deadband region (A) at low rotational velocities. The application of mechanical dither breaks the deadband region up into smaller fragments (B) that occur at input rates equal to harmonics of the dither frequency ω_d. (Adapted from [2].)*

prototype, use four mirrors to create a square path.) The mirrors are usually mounted to a monolithic glass-ceramic block with machined ports for the cavity bores and electrodes. The most stable systems use linearly polarized light and minimize circularly polarized components to avoid magnetic sensitivities [2]. The approximate quantum noise limit is due to spontaneous emission in the gain medium [11], representing the best-case scenario of the five general gyro configurations outlined earlier.

As shown in Figure 2, dual anodes are generally incorporated to overcome Doppler shifts attributed to the otherwise moving medium within the laser cavity. In DC-excited plasma, the neutral atoms tend to move toward the cathode along the center of the discharge tube and toward the anode along the walls. This phenomenon is known as *Langmuir flow*; the laser radiation, being predominately along the tube centerline, thus experiences a net motion in the medium itself [8]. The opposed dual-anode configuration introduces a reciprocity in the Langmuir flow that cancels the overall effect, provided the anode currents are kept precisely equal.

The fundamental disadvantage associated with the active ring laser is a problem called *frequency lock-in*, which occurs at low rotation rates when the counterpropagating beams "lock" together in frequency [13]. This phenomenon is attributed to constrictions or periodic modulation of the gain medium, in conjunction with the influence of a very small amount of *backscatter* from the mirror surfaces [12]. The result is a small deadband region (below a certain threshold of rotational velocity) for which there is no output signal (see Figure 3A). Above the lock-in threshold, output approaches the ideal linear response curve in a parabolic fashion.

The most obvious way to solve this problem is to improve the quality of the mirrors, thereby reducing the resulting backscatter. Again, however, perfect mirrors do not exist, and some finite amount of backscatter will always be present. Martin [2] reports a representative value of 10^{-12} the power of the main beam, enough to induce frequency lock-in for rotational rates of several hundred degrees per hour in a typical gyro with a 20-cm perimeter. A more practical technique is to incorporate some type of biasing scheme to shift the operating point away from the deadband zone.

Mechanical dithering is the least elegant but most common and effective biasing method, introducing the obvious disadvantages of increased system complexity and reduced MTBF associated with moving parts. The entire gyro assembly is rotated back and forth about the sensing axis in an oscillatory fashion (±100 arc-seconds at 400 Hz typical), with the resulting response curve shown in Figure 3B (page 57). State-of-the-art dithered active ring-laser gyros have a scale factor linearity that far surpasses the best mechanical gyros. Dithered biasing, unfortunately, is too slow for high-performance systems (e.g., flight control), resulting in oscillatory instabilities [2]. Mechanical dithering can also introduce crosstalk between axes on a multiaxis system, although some of the unibody three-axis gyros use a common dither axis to eliminate this possibility [2].

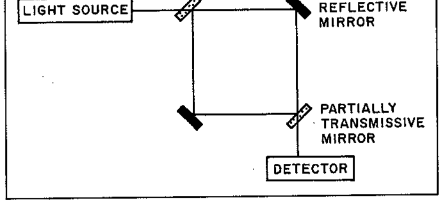

Figure 4. *This passive ring resonator gyro has a laser source external to the ring cavity, eliminating problems peculiar to active gyros.* (Adapted from [10].)

Buholz and Chodorow [14], Chesnoy [15], Christian and Rosker [16]), and Dennis et al. [17] discuss the use of extremely short-duration laser pulses (typically 1/15 of the resonator perimeter in length) to reduce the effects of frequency lock-in at low rotation rates. The basic idea is to minimize the cross coupling between the two counterpropagating beams by limiting the regions in the cavity where the two pulses overlap. Wax and Chodorow [18] report a two order of magnitude improvement in performance through the use of intracavity phase modulation. Other techniques based on nonlinear optics have been proposed [12], including an approach by Litton that applies an external magnetic field to the cavity to create a directionally dependent phase shift for biasing [2]. Yet another solution to the lock-in problem is to remove the lasing medium from the ring altogether, effectively forming what is known as a passive ring resonator.

PASSIVE RING RESONATOR GYROS

The *passive ring resonator* gyro makes use of a laser source external to the ring cavity (see Figure 4), and thus circumvents the frequency lock-in problem that arises when the gain medium is internal to the cavity itself. The passive configuration also eliminates problems arising from changes in the optical path length within the interferometer due to variations in the index of refraction of the gain medium [8]. The theoretical quantum noise limit is determined by *photon shot noise* and is slightly higher (i.e., worse) than the theoretical limit seen for the active ring laser gyro [11].

Classical implementations of mirrored

optical resonators patterned after their active ring predecessors suffered from inherently bulky packaging in comparison to the alternatives offered by fiber-optic technology. These fiber-optic derivatives also promise the additional advantage of longer-length multiturn resonators for increased sensitivity in smaller, rugged, and less expensive packages. As a consequence, the *resonant fiber-optic gyro* (RFOG), to be discussed in Part II, has emerged as the most popular of the resonator configurations [19].

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