1

Pre-history of Large Ring Lasers

1.1 The Sagnac Effect and Some Early Experiments

The reader is doubtless familiar with the 1881–1887 Michelson–Morley experiments in which Albert Michelson, together with Edward Morley, famously attempted (repeatedly with ever greater accuracy; first in Potsdam and subsequently in Cleveland) to prove the existence of the aether wind – the supposed medium that permeated space allowing for the propagation of light. Ultimately, they failed to observe any fringe shift in their L-shaped interferometer – a finding in direct conflict with accepted scientific theory at that time and which ultimately culminated in the development of the theory of general relativity. The early history of the Sagnac effect is also intimately associated with that intensive search for the aether around the end of the 19th century.

Following on from the Michelson and Morley experiment, a fundamental question of the time was whether the Earth dragged the aether along with it, as it moved through space. In order to investigate such a possibility, the English physicist Sir Oliver Lodge carried out careful experiments [7, 139, 140] involving rapidly rotating disks in order to induce a dragging of the aether. Both Michelson and Lodge firmly believed in the aether theory – Lodge going so far as to believe that the spirit world existed within it. It is therefore something of an irony that it was their experiments that constituted the primary evidence that it did not exist. Lodge's 1883 and 1887 experiments were serious undertakings involving one meter diameter steel disks spun on the vertical axis of an electric motor at speeds of up to 3000 rpm. The light path of an interferometer then passed between the beams, the idea being that if the aether were dragged along with the spinning disks, this would show up as a fringe shift in the resultant interference pattern. As with the Michelson and Morley experiments in the preceding decade, a null result was obtained.

A further experiment by George Sagnac demonstrated the absence of a *"whirling of the ether"* for a 20 m perimeter vertical ring within the error limits of $\frac{1}{1000}$th fringe,

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a conclusion from which was taken that no radial velocity gradient with non-zero curl existed within these error limits [7]. Furthermore, it is interesting to note that Franz Harress, a young scientist in Jena (Germany), who used a fast rotating glass prism ring (12.5 rev. per sec.) to investigate the dispersion properties of glass, came up with an observed fringe shift of

$$\Delta = \frac{2lq}{\lambda c}, \tag{1.1}$$

with q the angular velocity of the rotating body, l the light path inside the glass prisms, λ the optical wavelength and c the velocity of light in a vacuum [120]. For the simplified case of a circular structure, $l = 2\pi r$ and $q = 2\pi r\omega$, so that Eq. 1.1 becomes

$$\Delta = \frac{8\pi A}{\lambda c}, \tag{1.2}$$

with A the enclosed area. This equation turns out to be what is today known as the *Sagnac Equation*. However, Harress and his colleagues did not recognize its significance. Since they assumed aether was dragged along with the prism ring, they misinterpreted his measurement result as the drag coefficient. Incidentally, it is noteworthy that this drag coefficient could not be derived with this kind of apparatus, and the correct interpretation of this signal as a Sagnac fringe shift was excluded implicitly by the assumption of dragged aether. In retrospect, his measurements were more precise than those of George Sagnac, who was the first to correctly combine the theoretical expectations with an experiment. He generated a coherent beam of light, which he guided around a contour with a predetermined area of 0.086 m^2. The entire apparatus was then rotated with a frequency of approximately 2 Hz [173, 174]. With the help of a beam splitter and several mirrors, he managed to generate two counter-propagating beams, passing them around the same optical path. He observed a shift in the interferogram of 0.07 ± 0.01 fringes and found that the measured shift was directly proportional to the rate of rotation. Further, he established that the effect that now bears his name does not depend on the shape of the optical circuit or the center of rotation. His technical skill in building the instrument with sufficient mechanical stability such that no bending of optical components under the substantial centrifugal forces had an impact on his measurements has to be admired. Finally, we remark that his observation, referred to as the *Sagnac effect* today, would require an aether at rest and was in contradiction with Michelson's findings. Again, it is an irony of history to note that G. Sagnac performed his experiment in order to prove the existence of the aether. Furthermore, his experiment can be described either by the theory of relativity or by a classical aether theory, so that it is not possible from this experiment to decide which of the theories is right

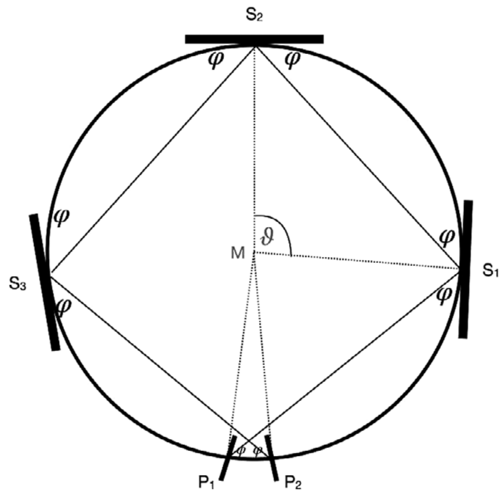

Figure 1.1 Schematic reproduction of the thought experiment by Max von Laue, used in his proof that an experiment, such as the historical Sagnac experiment, produces the same result, irrespective of the assumed theory [228].

or wrong [129]. As a result of these collective experiments, the aether theory was given up.

In 1911, Max von Laue presented a thought experiment [228] on the propagation of light around a rotating circular body (see Figure 1.1), which he solved by geometric considerations in the framework of special relativity, for the case of a preferred frame theory, and in classical electrodynamics. In all cases he obtained the same expression for the experienced difference in propagation time between counter-propagating light beams, namely

$$\Delta\tau = \frac{4A}{c^2}\Omega \sin\varphi, \tag{1.3}$$

which corresponds exactly to the result of George Sagnac. A is the area, c the velocity of light, Ω the experienced rate of rotation and φ the latitude in Eq. 1.3. A full description of the Sagnac effect is based on general relativity [61]; however, as worked out by von Laue, a classical interpretation yields the same result [95, 105]. A simplistic derivation is possible by considering the physically limiting case of a circular beam path of radius R with counter-propagation beams contained within [149]. In the absence of an externally imposed rotation, we may write for the round trip path length L for either beam and their time travel time t:

$$L = 2\pi R \tag{1.4}$$

$$t = \frac{L}{c} = \frac{2\pi R}{c}. \tag{1.5}$$

If the body of this hypothetical interferometer is subject to a physical rotation in the clockwise sense and has an angular velocity of Ω, we now write for the clockwise sense of propagation:

$$L_{\mathrm{cw}} = 2\pi R + \Omega R t_{\mathrm{cw}} \tag{1.6}$$

$$t_{\mathrm{cw}} = t + \frac{\Omega R t_{\mathrm{cw}}}{c}. \tag{1.7}$$

With the aid of Eq. 1.5, we get

$$t_{\mathrm{cw}} = \frac{2\pi R}{c} + \frac{\Omega R t_{\mathrm{cw}}}{c} \tag{1.8}$$

and therefore

$$t_{\mathrm{cw}} = \frac{2\pi R}{c - \Omega R}. \tag{1.9}$$

Similarly we may write for the counter-propagating beam travelling in the counter-clockwise direction:

$$L_{\mathrm{ccw}} = 2\pi R + \Omega R t_{\mathrm{ccw}} \tag{1.10}$$

$$t_{\mathrm{ccw}} = \frac{2\pi R}{c + \Omega R}. \tag{1.11}$$

Thus, the path difference is

$$\Delta L = c(t_{\mathrm{cw}} - t_{\mathrm{ccw}}) = 2\pi R \left[\frac{1}{c - \Omega R} - \frac{1}{c + \Omega R}\right] \tag{1.12}$$

$$= 2\pi R c \frac{2\Omega R}{c^2 - \Omega^2 R^2} = \frac{4\pi R^2 \Omega}{c} \frac{1}{\left[1 - \frac{R^2\Omega^2}{c^2}\right]} \tag{1.13}$$

$$\approx \frac{4\pi R^2 \Omega}{c}. \tag{1.14}$$

The observed phase difference can then be written as

$$\delta\phi = 2\pi \frac{\Delta L}{\lambda} = \frac{8\pi^2 R^2 \Omega}{\lambda c} = \frac{8\pi A \Omega}{\lambda c}. \tag{1.15}$$

Including the dependence upon the orientation of the interferometer body to the rotation axis, we have:

$$\delta\phi = \frac{8\pi A}{\lambda c} \mathbf{n} \cdot \mathbf{\Omega}, \tag{1.16}$$

where **n** is the normal vector upon A. Equation 1.16 relates the obtained phase difference to the rate of rotation of the entire apparatus and can be interpreted as the gyroscope equation [208]. Fiber optic gyros (FOG) are modern embodiments of this kind of optical gyroscope. Because glass fibers with a length of several hundred meters are used, the scale factor can be made very large by winding the fiber into a coil, and the rotational sensitivity is therefore much larger than for Sagnac's experiment. With L the length of the fiber and R the radius of the resultant coil, one obtains

$$\delta\phi = \frac{4\pi LR}{\lambda c}\mathbf{n} \cdot \mathbf{\Omega}. \tag{1.17}$$

The rotation rate of the Earth alone would have generated a fringe shift of $\approx 0.4 \times 10^{-6}$ on Sagnac's historic instrument, which is well outside the range of sensitivity of the comparatively small apparatus. Based on Sagnac's experiment, it was possible to estimate the size required for an instrument capable of resolving an angular velocity of ≈ 50 μrad/s, which corresponds to the Earth's rotational velocity as it would be experienced at mid-latitude. The goal of course was to measure a very small, nearly constant angular velocity. The experiment was not intended to prove the existence of the Earth's rotation as such.

1.2 The 1925 Michelson, Gale and Pearson Experiment

As early as 1904, Michelson laid forth the conceptual essence of a large scale, closed path, interferometric measurement of the relative motion of the Earth and the aether [147], as well as a method to calibrate the proposed device. The idea was put into practice at Clearing, west of Chicago, in 1925 – the area currently home to Chicago Midway airport. It is very noteworthy that the effort was still done in pursue of the aether. For this mammoth experiment, 12 inch water pipes were utilized to create an evacuated, rectangular optical path 2010 ft by 1113 ft (approximately 613×339 m) [148]. The pipes were joined to cast-iron corner boxes, with a degree of mechanical decoupling provided for by flexible joints. As the entire beam path was evacuated, screw and lever systems were used to align the mirrors. By all accounts [201], Michelson was ill at the time, and the experiment proceeded through the efforts of Henry Gale and Fred Pearson. Figure 1.2 shows a design draft of this experiment. Highly reflecting mirrors were positioned at D, E and F, while the plates at A, B and C acted as beamsplitters via the thin optical coatings applied. The critical feature of this experiment was that the rotation to be measured (the Earth's rotation) could not be switched off or reversed in its sense of rotation. Michelson and Gale had to prove that any observed fringe shift was indeed a measurement quantity and not an artifact generated from the finite thickness of the beamsplitter

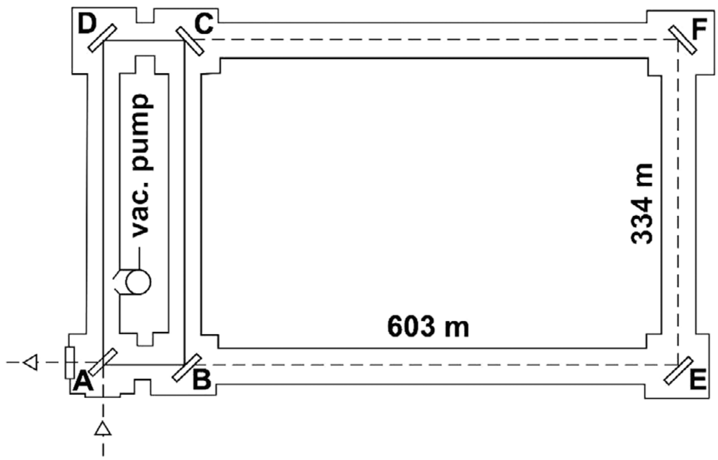

Figure 1.2 Schematic of the 1925 Michelson and Gale experiment. The optical interferometer had a length of 603 m and a width of 334 m. (Reprinted with permission of AIP Publishing from [182], ©2022, American Institute of Physics)

or multiple reflections in the interferometer itself. Thus the set of fringes generated by the circuit ABCD was used as a calibration point, since the area enclosed by this section was insufficient to generate a measureable fringe shift. The main circuit ADEF generating the measurement quantity, with the rotation rate of the Earth at the location of Clearing (Illinois, USA) generating a shift of 0.23 fringes, measured with an uncertainty of no more than 0.005 fringes. This corresponds to a measurement error of only 2%. This was a huge experimental feat.

1.3 The Advent of Lasers: The 1963 Macek and Davis Ring Laser

It is arguably the case that by the 1950s, optics as a field had stagnated somewhat. This changed radically when a technique for coherent light amplification by stimulated emission was found, aside from anything else giving breath and form to both non-linear optics and quantum optics. On the afternoon of May 16, 1960, Theodore Maiman demonstrated the first working laser, made using a gain medium consisting of a 2 cm rod of ruby (Al_2O_3 doped with trivalent chromium – the optically active, dopant ion) [144]. Shortly thereafter followed lasers utilizing a gaseous discharge which converted electrical energy directly into optical energy, as opposed to the optically pumped ruby laser [108].

It appears that the first idea of using the Sagnac effect in a resonant cavity to measure rotation dates back to the late 1950s with the work of Clifford Heer, as documented in a patent disclosure dated October 7, 1959 [89, 90], although the work of Adolph Rosenthal at a comparable time [167] must surely be acknowledged.

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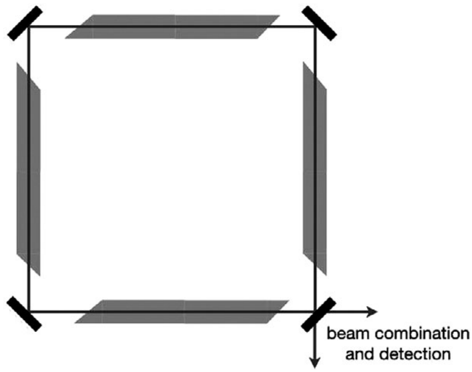

Figure 1.3 A design sketch of the first laser gyro at around 1963. Four large gain tubes with Brewster windows were placed around the sides of the square cavity, in order to compensate for the significant losses of the mirrors. The system operated on an infrared transition at $\lambda = 1.153\ \mu\text{m}$ [142].

In the account given by MacKenzie [143], Warren Macek of the Sperry Gyroscope Company was in the audience when Rosenthal gave his presentation at the 1961 annual meeting of the Optical Society of America [167]. Macek was a member of an optics group started at Sperry as early as 1957 and already had ambitions to build rotation sensing devices using lasers. By all accounts, internal proposals of this nature were not well met by the Sperry management, and perhaps as a consequence, what was to ultimately become the world's first laser gyroscope was put together with pre-existing plasma tubes and associated equipment. Figure 1.3 depicts a block diagram of this very first laser gyroscope. High quality mirrors were difficult to obtain, and therefore three dielectric mirrors and one curved gold mirror were used to form the cavity (the gold mirror having been coated by a relative [89, 143]). Macek's one meter square gyroscope was constructed from individual sealed plasma tubes with Brewster windows at each end. Radio frequency excitation fueled the gain medium in a cavity designed to support amplification at 1.15 μm on the $2s_2 \longrightarrow 2p_4$ transition of neon in a helium–neon gain medium. Having 20 intracavity surfaces, rotation sensing was only achieved on a mechanical turntable, a feat first achieved in late december 1962 (a mere two years after the first demonstration of the HeNe laser itself – see Chapter 2). Beat notes were observed between 1 and 40 kHz, limited by the available equipment.

Unlike earlier Sagnac interferometers, such as the Michelson, Pearson and Gale ring [148], the ring laser gyroscope converts phase information measured via a fringe shift into frequency, since the fractional path length change experienced under the influence of an externally imposed rotation is equal to the fractional frequency shift experienced by the counter-propagating beams in a resonant cavity.

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The measurement of a frequency splitting comes with a concomitant increase in sensitivity of many orders of magnitude. The technological significance of their achievements were not lost on Macek and his co-workers, as the final paragraph of their seminal 1963 paper [142] makes clear: "The principle demonstrated in this experiment may be utilized for rotation rate measurement with high sensitivity over an extremely wide range of angular velocities. Such sensors would be self-contained, requiring no external reference."

Following the demonstration of the laser gyroscope, research programs in the USA, Soviet Union, France and the UK were initiated. Of these, most notable was the long term effort by researchers at Honeywell, which included Frederick Aronowitz and Joseph Killpatrick. The objective at Honeywell was commercial success in the medium grade market for military and commercial aircraft. To achieve this, they came up with the, now familiar, triangular configuration drilled into a solid block of quartz (which evolved into a glass ceramic construction of firstly Cer-Vit and latterly Zerodur). In their 'monolithic' design, the laser discharge (which filled the entire cavity) was excited via a single cathode and double anode structure. In addition, they introduced the mechanical dither approach to overcome backscattering from the intra-cavity mirrors, which prevents small gyros from rotation rate sensing at low input rates. In fact, a mechanically dithered gyroscope developed at Honeywell in 1964 was probably the first laser gyro to detect the Earth's rotation. By 1966, Honeywell could claim the first flight test of a laser gyro system. Ring laser gyroscope-based inertial navigation systems require 0.01°/h accuracy and went into large scale civilian airline service in 1981. The modern market for commercial navigational gyroscopes is dominated by companies such as Honeywell, Northrop–Grumman, Thales, iXBlue and Sagem, who supply Airbus and Boeing, among other aircraft manufacturers. The overall gyro market is valued at well over 1.5 billion US dollars at the time of writing, albeit that this includes all sensor types, not just ring laser gyros.

1.4 Passive Optical Gyroscopes

Another approach for precise interferometric measurement of rotation is the externally injected excitation of the TEM_{00} cavity mode of a ring resonator experiencing rotation. This method was explored by Ezekiel and Balsamo in 1977 [71], since it was believed at the time to be free from the frequency lock-in issue as well as deleterious effects associated with an intra-cavity gain medium, such as bias drift and scale factor variations. A block diagram of the setup is shown in Figure 1.4. In their experiment, the beam of an external, single frequency HeNe laser was divided in two by a beamsplitter. Each beam was offset in frequency by an acousto-optical modulator to match the respective cavity modes of the clockwise and counter-clockwise senses

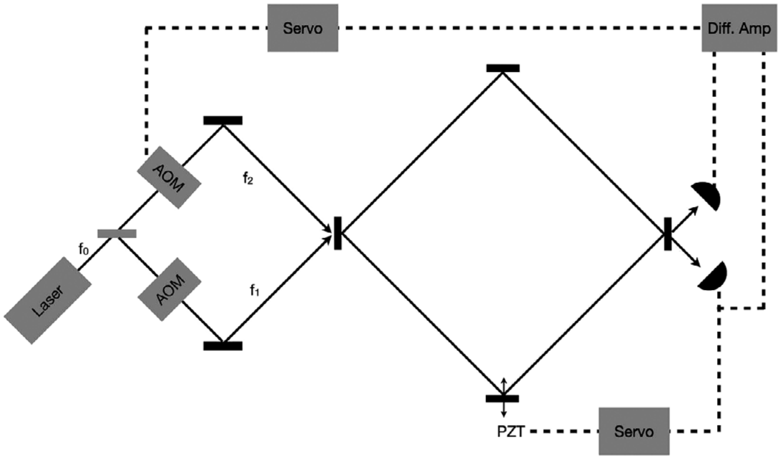

Figure 1.4 A simplified schematic of the externally excited passive resonator gyroscope of Ezekiel and Balsamo [71].

of propagation of a square Fabry–Perot cavity, and the polarization was aligned with one of the polarization axes of the resonator. Both offset frequencies were derived from a stable low noise radio frequency RF oscillator, so that the effective frequency jitter was caused by the laser source and was therefore identical for both counter-propagating beams and hence cancels out in the interferogram when the beat note Δf is evaluated to obtain the rate of rotation Ω. In the ideal case, Ω is strictly proportional to Δf and scales with the area enclosed by the light path. By dithering the resonance frequency of the cavity, a feedback loop was used to lock the resonator to the external laser beam injected into the cavity in the clockwise direction. A second feedback loop then adjusted the offset of the second laser beam to hit the resonance of the cavity in the counter-clockwise direction.

Such an experiment, although conceptually simple, comes with numerous hurdles in practice. Free space, external injection requires very careful alignment and mode matching of the beam from the external laser source to the passive cavity, to ensure the avoidance of high order transverse modes (a particular issue as the passive cavity gets larger). Furthermore, laser gyros rely on common mode rejection to achieve their sensitivity; again meticulous alignment is required to ensure and maintain coincident counter-propagating beam paths. Probably the most serious drawback of passive gyros is the fact that the cavity resonance is of the order of several hundred Hz wide. Active ring laser gyros, in comparison, generate a linewidth In the regime of 10 μHz. A consequence of this is that passive cavities with external excitation generally have a lower resolution and poorer common mode noise rejection. For an instrument size of 0.49 m^2, a sensitivity limit of about

2.4×10^{-8} rad/s for 100 seconds of integration was achieved [175]. Although this concept was expected to be free of lock-in behavior, it was later shown that the lock-in effect was similar to the effect seen in active ring laser gyroscopes, however only shifted to the two feedback loops [237].

Fiber ring interferometers were first reported in 1976 as low loss, single mode fibers became available [223, 224]. The significance of single mode fibers is that different modes have different effective path lengths and propagation velocities; thus a multi-mode fiber will not maintain the coherence required for a high contrast Sagnac interference pattern. By the early 1980s, research at both Stanford and MIT led to reports of fiber optic gyroscopes for fiber lengths up to 900 m [22, 23, 51, 199]. Both HeNe and semiconductor diode (GaAs) lasers were used as external sources in the various measurements, the best results achieving a rotational sensitivity of around 0.1°/h for 30 seconds of averaging (which is of the order of $5 \times 10^{-3}\ \Omega_E$) with near-photon noise-limited behavior [51]. By 1982, fiber optic gyroscopes having a sensitivity suitable for inertial navigation requirements had been developed [130]. Single mode fiber resonators were also developed in that year [211], and subsequently, Ezekiel's group at MIT reported the development of a passive fiber-optic ring resonator [146] constructed from 3.1 m of fiber formed into a ring and closed off with an evanescent wave coupler. A single frequency HeNe laser operating at 632.8 nm was used as the externally injected source, which was split into two beams, and either beam was frequency shifted by acousto-optical modulators as in the 1977 Ezekiel and Balsamo free space ring resonator experiment discussed above. The influence of backscatter was minimized through the use of phase modulation of one of the input beams. These initial measurements achieved a rotational sensitivity of 0.5°/h for one second of averaging.

1.5 Large Gyroscope Experiments in the Early 1980s

The early suggestions to measure general relativistic precessions using gyroscopes date back to shortly after Einstein advanced the theory of general relativity in 1915. In the 1930s Blackett examined the prospect of constructing a laboratory gyroscope for such a purpose, concluding that with the technology of the time it was not possible [69]. With the advent of satellite technology, the situation had changed, and renewed proposals were put forward by Schiff [179] and others. The timely coincidence of proposals to measure relativistic effects with gyroscopes and the development of the laser, and subsequently the laser gyroscope, did not go unnoticed, as the Ezekiel and Balsamo experiment [175] (Section 1.4) makes quite clear. In 1982, The Frank J. Seiler Research Laboratory (FJSRL) of the USAF Academy in Colorado Springs commenced a substantial program to develop a passive resonant ring laser gyroscope (PRRLG), building on the work of Ezekiel and Balsamo [71]

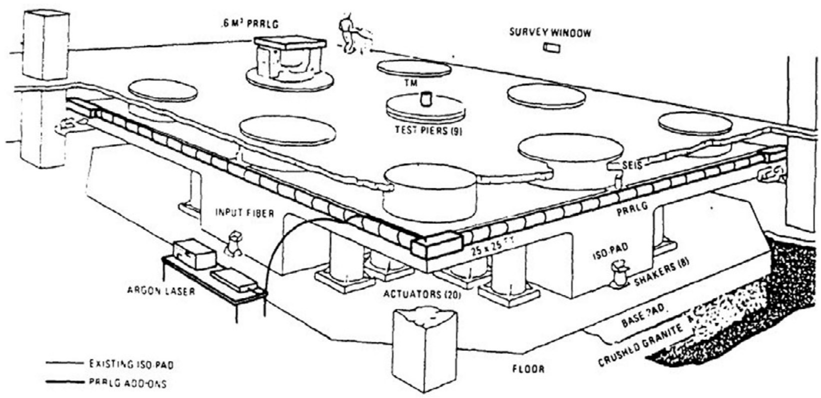

Figure 1.5 Schematic representation of the FJSRL passive resonant ring laser gyroscope project. (Reprinted from the final report on Optical Rotation Sensors JSRL-TR-86-0002 [169])

and motivated by Balsamo's arrival at FJSRL. While the primary objective of this program was clearly military in nature, a secondary objective was to consider the use of large gyroscopes for the study of geophysical phenomena as these were of interest to the Air Force Geophysical Laboratory and the Defense Mapping Agency Geodetic Survey Squadron.

The FJSRL approach was that of the passive ring resonator having the excitation source external to the cavity, closely following the Ezekiel and Balsamo experiment. This appears to have been motivated by the erroneous belief that such an approach avoids the lock in phenomenon, since the laser is external to the cavity. The concept was to initially develop a 0.62 m^2 feasibility model followed by a larger ring of approximately 60 m^2, a sketch of which is shown in Figure 1.5. Both would be placed on a large isolation test pad, providing seismic stability to the ring body but also to provide known input signals for calibration purposes [29, 202, 203]. This program was exceedingly ambitious for the time, having the objective of achieving performance at a resolution of 10^{-10} of the Earth's rotation. The isolation platform itself was 7.62 meters square and constructed from steel-reinforced concrete supported by 20 (pressurized air fed) pneumatic actuators. The excitation source was to be initially a stabilized, single frequency HeNe laser, to be replaced by an argon laser (having an expected linewidth of less than 3 kHz) in due course for the higher photon count. Light from the excitation source was to be fed to the ring via optical fiber, thereby isolating the cavity from any mechanical disturbance induced by the argon laser, which requires high flow rate, water cooling. The large PRRLG was intended to occupy the full perimeter of the iso-pad, with Zerodur structurally stabilized arms, and included active perimeter control. The optical beam path was to be evacuated, and significant work went into the appropriate mode matching optics required to minimize excitation of high order transverse resonator modes [14].

The large PRRLG was never completed, its stop order given on November 27, 1985. It appears the project fell victim to the levels of manpower and budget required to complete the task, together with the prerogatives of the Air Force Office of Scientific Research [170] at the time. What is impressive is the legacy left behind in the literature and mostly resulting from the 20 or so support projects conducted by other institutions, such as the work conducted at the University of New Mexico on quantum detection limits, relativistic experiments and gravitational wave detection, to give one example. It is further noted that two of the scientists involved in the FJSRL experiment had a hand to play in the large ring laser experiments beginning in the late 1980s in New Zealand. These were Hans Bilger, who was involved in the early experiments on ring lasers sized 1 m^2 and below, and Robert Dunn, who was involved in the 'Ultra-G' big ring program at the very beginning of the 21st century. Both of these scientists brought very considerable expertise to the big ring, active gyro programs that followed the FJSRL experiment.