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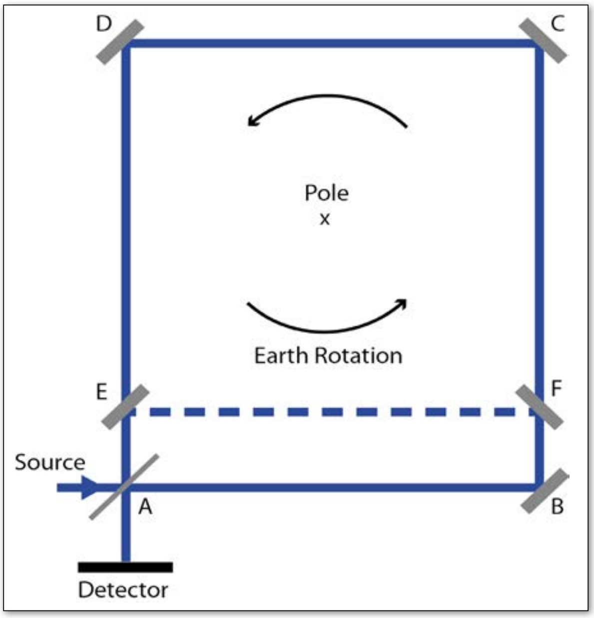
Ring lasers – a brief history

Used these days in inertial navigation, ring lasers are also used in recording the tiniest variations in the Earth's spin, as well in detecting earthquakes and even the drift of continents. How did it all begin?

Back in 1914, Frenchman Georges Sagnac [1] built an interferometer in the shape of a polygon of mirrors in which counter-propagating waves from the same intense light-source could demonstrate a phase shift between the clockwise and the anticlockwise propagating waves (see figure 1).

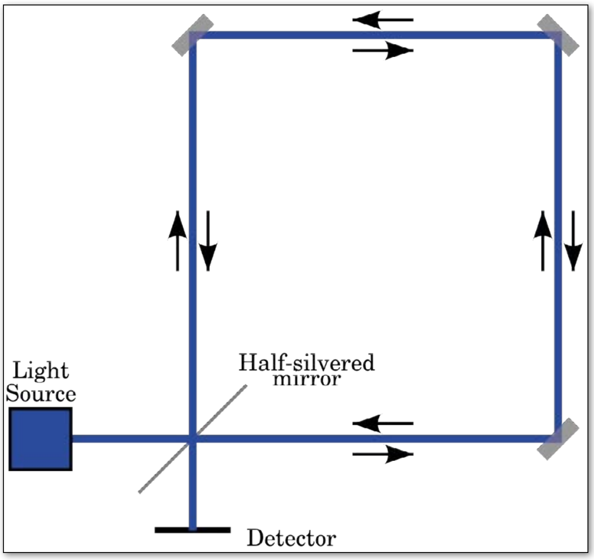
When stationary, the two modes are degenerate, but if set into rotation, one lot of light waves from the beam-splitter are chasing the mirrors while the other lot are running into them, thereby producing a phase difference between the two beams. What Sagnac had intended to demonstrate was the speed of light relative to the "Luminiferous Ether" (which was shown to be non-existent by Einstein's Special Relativity).

The time difference effect, now named after Sagnac, may be shown to be given by [2]: $\Delta t = 4\boldsymbol{A} \,.\, \boldsymbol{\Omega}/c^2$ where $\boldsymbol{A}$ is the area (vector) of the polygon enclosed by the interferometer mirrors, $\boldsymbol{\Omega}$ (vector) is the angular velocity of the interferometer, and c is the velocity of light. In a passive interferometer, the time difference shows up as a phase difference: $\Delta\phi = 8\,\pi\boldsymbol{A} \,.\, \boldsymbol{\Omega}/\,\lambda c$ where λ is the wavelength of the light source. The irony is that these formulae are true in both an ether-theoretic picture and in Special Relativity, so that the experiment didn't, in fact, demonstrate anything. This was recognised by Albert Michelson who proceeded to build his well-known Michelson-Morley experiment that did, of course, demonstrate the correctness of the Einstein theory.



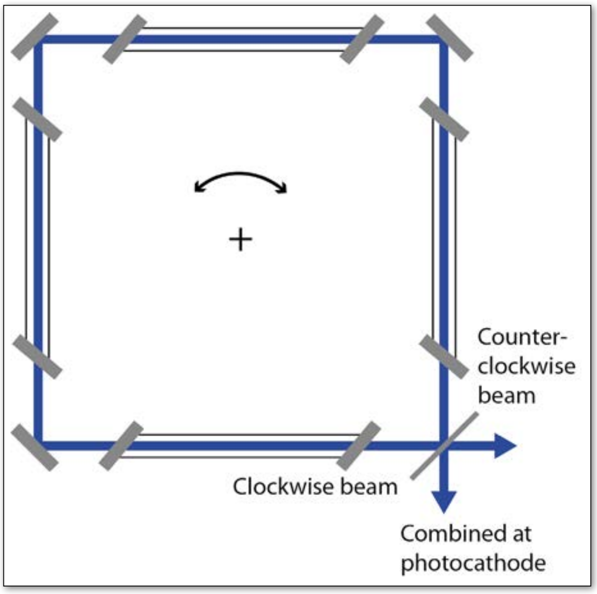
▲ **FIG. 2:** Schematic of the Michelson-Gale Experiment. Here the phase difference between light waves exiting the large and the small rectangles is detected. With a perimeter of 1.9 km, this set-up was large enough to detect the angular velocity of the Earth.

▼ **FIG. 1:** Schematic of a Sagnac Interferometer. If set into rotation, a phase difference between the two beams will show up. (Image credit Krishnavedala, CC BY-SA 3.0.)



However, in 1925, many years after the more famous Michelson-Morley experiment, Michelson and Gale [3] did indeed perform a "heroic" experiment aimed at detecting the Earth's rotation, by means of a huge rectangular Sagnac interferometer 612 × 339 meters in size, built in the countryside near Chicago, from evacuated 12-inch sewer pipes. I say "heroic" because the observed fringe-shift was only 0.230 ± 0.005 of a fringe, but in good agreement with the theoretical prediction (see figure 2).

(In case you were wondering, they observed the difference in fringe-shifts between the interferometers (ABCDA) and (ABFEA), *i.e.*, changing the area enclosed). There are of course other ways of proving that the Earth rotates, even



▲ **FIG. 3:** Schematic of a Ring laser.

without reference to the fixed stars, including the famous Foucault pendulum.

There matters stood until the year 1962 when a very interesting paper by Rosenthal [4] appeared in the Journal of the Optical Society of America proposing the insertion of active media (*e.g.*, Helium-Neon) inside a Sagnac (*i.e.*, a polygonal) interferometer which would then turn into a Ring Laser- see figure 3.

In such a laser, two modes would co-exist, namely the clockwise and the anticlockwise – normally degenerate in a stationary frame. However, when in a rotating frame, the phase difference between the two modes would turn into a frequency difference, *i.e.*, a detectable beat note. The optical frequency difference between the two modes in the polygonal laser (which may be triangular or square) is given by [2]: $\delta f = 4A\,\Omega \cos\theta/\lambda P$ where A is the area enclosed, as before, Ω is the rotation rate; while θ is the angle between the rotation axis and the normal to the polygon of mirrors, and P is the perimeter of the polygon.

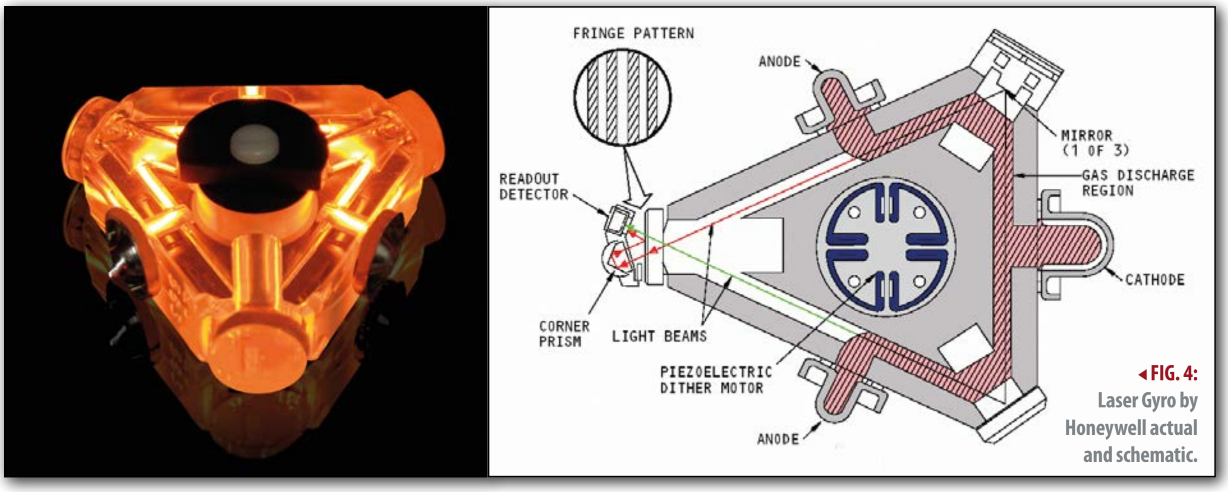
($A\,\Omega \cos\theta$) is of course, ($A\,.\,\Omega$), showing θ explicitly, so that the beat frequency is seen to be sensitive to both Ω and to θ, and can thus measure variations in either.

This exciting idea, for *active* Sagnac Interferometry, made everyone sit up and take notice and sure enough, it was followed less than a year later by a paper by Macek and Davis [5] demonstrating its feasibility. Thus was born the Ring Laser.

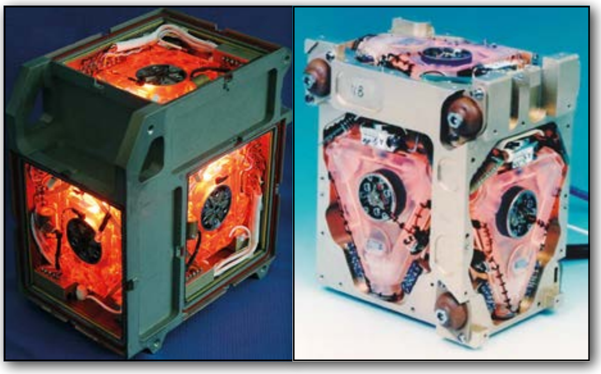
The military potential of a rotation sensor (with no moving parts), *i.e.*, a Laser Gyro, was promptly recognised and further development became classified secret, so the scientific literature on the subject went completely silent! Rapid progress followed all over the world and by the 1970s the Ring Laser Gyro became patented and openly published again in various forms, see figure 4a and b.

One of the shortcomings of compact ring lasers is the phenomenon of mode locking at low rotation rates. There is a minimum angular velocity below which the clockwise and anticlockwise modes simply lock together, causing zero frequency difference in the output. This is caused by parasitic phenomena, *e.g.*, back-scattering from imperfect mirrors, and places a lower limit on measurable rotation rates. What emerged as the standard solution to this problem was in the form of motor-driven "dithering" about each of the axes, *i.e.*, artificial rotation back and forth through a small angle about zero. The resultant sinusoidal modulation of the output is easily subtracted from the signal. Highly refined complete inertial navigation packages (see figure 5a and b) became commercially available and have been in widespread use since the 1980's, for example in the Boeing 747 and all airliners since (and in all missile guidance systems, of course).

An interesting variant of the Sagnac interferometer is the Fibre Optic interferometer in which the polygon of mirrors is replaced by a large number of turns of optical fibre in which the contra-rotating beams propagate, as in figure 6. Thus a very large included area A is made possible in a compact size, allowing the realisation of compact Fibre Optic Gyros – also available commercially.



◀ **FIG. 4:** Laser Gyro by Honeywell actual and schematic.



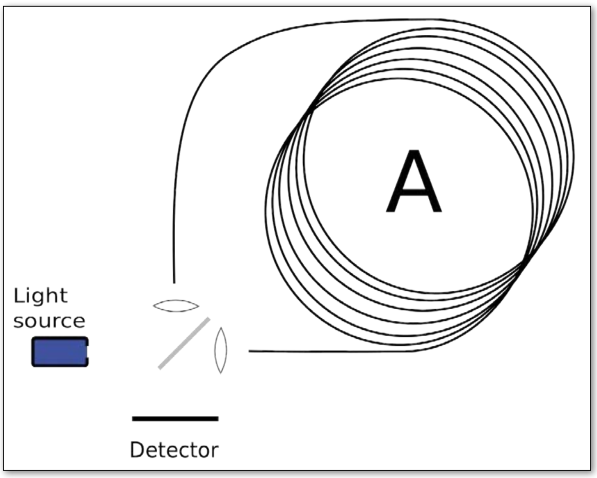
▲ **FIG. 5:** Complete inertial navigation systems (note in the middle of each triangular ring laser the "dithering" motor).

But the story of the ring laser as a rotation sensor doesn't end there. In the early 1990s, Professor Geoff Stedman of Canterbury University in Christchurch, New Zealand, decided to investigate its potential in measuring tiny variations in the Earth's spin caused by various geophysical sources, such as earthquakes, tidal effects, and diurnal polar motion [6].

He built a series of large area ring lasers (with higher and higher sensitivities), first in the Physics building and later in a Second World War bunker, in the New Zealand countryside, 30m below the ground. The first instrument, with an enclosed area of ~0.85 m^2, built in 1992, was followed by larger and larger rings, with enclosed areas of 1 m^2, then 3.5 m^2 the latter (first of a series) built in collaboration with the Technical University of Munich (TUM) and the German Federal Institute of Geodesy (BKG) (see figure 7 a and b).

A large instrument, built in the German countryside with input from the famous optical firm of Zeiss, was of 16 m^2 area and included various technical improvements, principally better mirrors and better laser beam control. In this way better and better performance was obtained, initially from 1 part in a million of the Earth's angular velocity to more recently approaching 1 part per billion. In this way not only could earthquakes be detected in detail but also their aftershocks. This is because of changes in the earth's moment of inertia caused by the slippage of blocks and other subtle seismic and geodetic effects. Other effects came to be investigated in detail such as the precession of the equinoxes, the Earth's Eulerian wobble - a consequence of the departure from its spherical shape - changes in the length of the day (measured in fractions of a millisecond per day) and so forth [7].

▼ **FIG. 6:** Schematic of a Fibre Optic interferometer. (Image credit D. Mcfadden, CC BY-SA 3.0.)



Ironically, the great earthquake of September 2010, and its aftershocks, that caused devastation in Christchurch were accurately documented by the underground interferometers and caused some damage at the installation in the cave. But the work continues, there and in Germany and elsewhere, with the aim of improving sensitivity to the point of being able to detect fundamental physical effects, *e.g.*, General Relativistic precessions of the rotating Earth, such as the Lense-Thiring effect. But basically, these large ring lasers may be regarded as components of an inertial navigation system for 'spaceship Earth.' ■

▲ **FIG. 7: (a)** The north arm of the University of Canterbury's UG-2 ring laser, situated in the Cashmere Caverns, New Zealand. **(b)** G (for "*Grossring*") Ring Laser in Bavaria, Germany. Both are situated underground to give thermal stability.

About the Author

Anthony Klein (AM, BEE, PhD, DSc, FAA) is an Emeritus Professor in the School of Physics of the University of Melbourne, where he held a Personal Chair in Physics until his retirement in 1998. He served as Head of the School of Physics, as President of the Australian Institute of Physics and as President of the Australian Optical Society.

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