approach to statistical mechanical systems in two dimensions.

Even more than the pure gluon gauge theories, the recent theories that incorporate quarks are pushing the limits of computer technology. Wilson, who has been interested in the Monte Carlo techniques from the beginning, is actively promoting the development of very much more powerful computers for this and many other areas of scientific calculations. Ironically theorists may have to wait for machines of greater capabilities, just as experimenters have in the past. —BGL

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Sensitive fiber-optic gyroscopes

Special relativity teaches us that no contrivance, mechanical or electromagnetic, confined in a closed vehicle, can detect the uniform rectilinear motion of that vehicle. But anyone who suffers from motion sickness can attest to the fact that nonuniform motion (acceleration or rotation) is a different story. Thus it is possible to direct ships, aircraft or missiles by inertial navigation systems, once an initial direction is established, without reference to magnetic compasses or radio beams.

Although Georges Sagnac demonstrated in 1913 that the rotation of a closed optical path about an axis normal to its plane changes the interference pattern of two light beams traversing the loop in opposite directions, navigational rotation sensors have until now been exclusively mechanical—spinning gyroscopes. But optical rotation sensors making use of the "Sagnac effect" are about to encroach upon this monopoly. Ring-laser gyroscopes developed by Honeywell will soon make their commercial debut aboard the new Boeing 767 and 757 airliners.

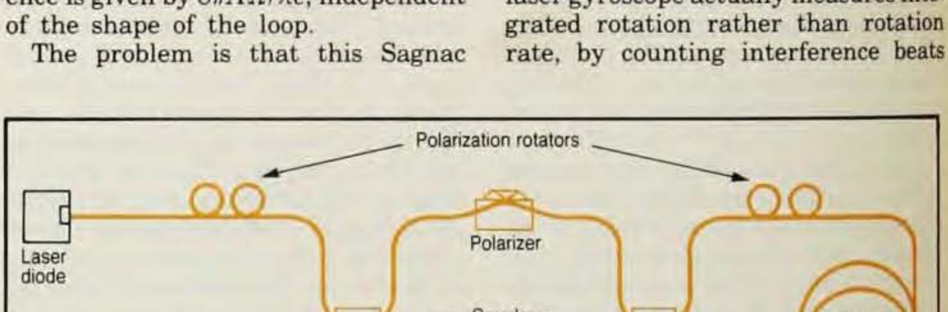
Two papers appearing in this month's *Optics Letters*[1,2] appear to promise that a second generation of optical rotation sensors—fiber-optics gyroscopes—is well on its way to achieving the sensitivity required for navigation. John Shaw and his colleagues at Stanford and an MIT group headed by Shaoul Ezekiel have constructed single-mode fiber-optic Sagnac gyroscopes with noise levels sufficiently low to permit detection of rotation rates about a hundredth of the Earth's rotation. Although this is still an order of magnitude less sensitive than what's needed for navigation (and what has already been achieved by ring-laser gyroscopes), both groups express confidence that no serious obstacles lie in the way of attaining a sensitivity of 0.01°/hour, a thousandth of "Earth rate." If this optimism is vindicated, fiber-optic gyroscopes would have a number of important practical advantages over ring-laser rotation sensors and mechanical gyros.

The Sagnac effect can be derived by a simple-minded argument that gives the Sagnac phase shift correctly to first order in v/c, the tangential velocity of the rotating optical loop divided by the speed of light. If two coherent light beams are made to travel in opposite directions around a stationary circular ring of radius R from a common source fixed on the ring, they will still be in phase when they return to the source. If we now rotate the ring and its light source with a tangential velocity v, the beam rotating with the ring will have an optical path longer than the counter-rotating beam by a distance $4\pi Rv/c$. For monochromatic light of wavelength λ, this would result in a Sagnac phase difference $\phi_s = 8\pi^2 Rv/\lambda c$ between the two beams after a single traversal of the loop, and hence an observable rotation-sensitive interference fringe pattern. For a single loop enclosing an area A and rotating with angular velocity Ω, the phase difference is given by $8\pi A\Omega/\lambda c$, independent of the shape of the loop.

The problem is that this Sagnac phase shift is exceedingly small for modest rotation rates. Shortly after Sagnac's original demonstration on a rapidly rotating table, Albert Michelson constructed a Sagnac interferometer, using about eight kilometers of evacuated sewer pipes, to detect the Earth's rotation. Even with an interferometer of such outlandish size, the Earth's rotation produces a phase shift at only about a tenth of a fringe, the smallest shift that could be detected with the instruments then available.

Ring-laser gyroscopes. With the development of the helium–neon laser (the first continuous-wave laser) in the early 1960's, a Sagnac rotation sensor became a practical possibility. W. M. Macek and D. T. M. Davis demonstrated the first such device at Sperry in 1963. In a ring-laser gyroscope, the He–Ne laser discharge tube is an integral part of the closed optical path of the interferometer. The usual end mirrors of the gas laser are replaced by the three or four mirrors that send laser light in opposite directions around the triangular or square optical path of the cavity. At rest, this laser system resonates in two degenerate modes—a clockwise and a counterclockwise traversal of the loop at a single frequency. When the system is rotated, the Sagnac effect breaks the degeneracy, producing a small frequency difference between the clockwise and counterclockwise modes.

This frequency difference is a direct measure of the rotation rate. The ring-laser gyroscope actually measures integrated rotation rather than rotation rate, by counting interference beats



Fully integrated fiber-optic gyroscope developed at Stanford is shown schematically. Infrared light from the GaAs laser diode is split by an integrated coupler into two components, which then traverse 580 meters of single-mode optical fiber (wound around a 14-inch-diameter spool) in opposite senses. Rotation of this fiber-optic loop causes a proportional "Sagnac" phase shift between the counter-rotating beams. The resulting rotation-sensitive interference pattern is sensed by the photodiode detector. With integrated polarizer, polarization rotators and piezoelectric phase modulator, the splice-free integrated fiber-optical path avoids the reflecting interfaces that contribute to noise, achieving a rotation sensitivity of 0.1°/hour.

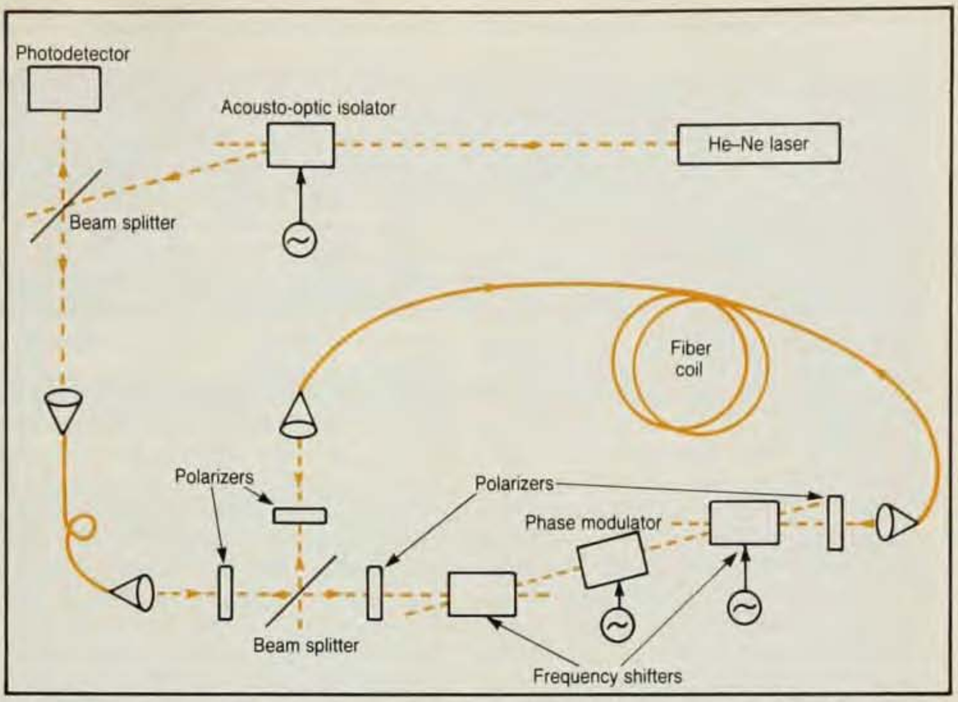
between the counter-rotating modes. To achieve the sensitivity necessary for navigation (10^{-3} of the Earth's rotation rate), the ring laser gyroscope must be able to detect a frequency difference of less than one part in 10^{17}—one of the most delicate measurements in all of physics, Ezekiel told us.

A problem that has plagued ring-laser gyros is "lock-in" at slow rotation rates. At such rates, where the Sagnac frequency shift is exceedingly small, the laser tends to lock the two counter-rotating modes into a single intermediate frequency. Honeywell has solved this problem by "dithering" the gyroscope, subjecting it to a continuous low-amplitude sinusoidal vibration so that it's never rotating at low rate long enough for lock-in to take hold. But dithering introduces its own problems. The mechanical vibration can generate cross-coupling of the three orthogonal gyroscope axes and other sources of error.

Fiber-optic gyroscopes. In 1976, when low-loss optical fibers had become available, Victor Valli and Richard Shorthill at the University of Utah constructed the first fiber-optic gyroscope. They were able to detect Sagnac phase shifts on a rapidly rotating table, but not until 1979 did groups at Telefunken (Ulm, Germany) and Thomson CSF (Orsay, France) succeed in getting the noise level in fiber-optic gyros down sufficiently to detect Earth rate.

If one can reduce the noise level enough to measure 10^{-3} of Earth rate, fiber-optic rotation sensors would in several respects be more attractive than mechanical or ring-laser gyroscopes. Mechanical gyroscopes suffer from acceleration sensitivity, to which the "massless" optical sensors are immune. Furthermore, mechanical gyros require a long start-up time as one waits for precession to die out, and they tend to drift as the spinning top winds down. They are also not very robust; the delicately suspended mechanical gyroscopes do not like to be turned through large angles.

Because the light source in a fiber-optic interferometer is external to the Sagnac loop, it does not suffer from lock-in, and hence requires no dithering. Fiber-optic gyroscopes are also likely to be more compact, rugged and inexpensive than ring-laser gyros. The light source of an integrated fiber-optic gyroscope would be a solid-state laser diode, or even a simple LED. Gas lasers are of course much larger and more expensive, and one has to worry about spurious phase shifts (Fizeau drag) resulting from the flow of the gas discharge. An integrated fiber-optic system does not require the careful alignment of mirrors and laser beams necessary for a ring-laser device. A fiber-optic navigational gyroscope could probably be fitted into a container the size and shape of a circular box of chocolates, Shaw told us.



MIT fiber-optic gyroscope has achieved the same rotation sensitivity as the Stanford device, despite retaining bulk optical components such as a gas laser, half-silvered-mirror beam splitters, polarizers, electro-optic phase modulator and acousto-optic isolator. Acousto-optic Bragg cells shift the frequencies of the counter-rotating beams to restore a null interference signal when the gyroscope is rotating. The net frequency shift becomes the calibration-free measure of rotation. Colored solid lines indicate the 200 meters of fiber-optical path.

Whereas in a ring-laser gyroscope the counterrotating beams pass repeatedly around the Sagnac loop that serves as the laser resonator, the light beams traverse a fiber-optic gyroscope only once before being made to interfere at a detector. But this fiber-optic Sagnac path can be made thousands of meters long by winding many turns of fiber around a circular spool less than a foot in diameter. Much enthusiasm was generated at a 1978 San Diego conference on optical rotation sensors, organized by Ezekiel and George Knausenberg (Air Force Office of Scientific Research), when a number of photon-noise-limit calculations were presented, indicating that fiber-optic sensors could in principle be made at least as rotation sensitive as ring-laser gyros.

In the afterglow of the San Diego conference, fiber-optic gyroscope experiments were undertaken in a number of laboratories in the United States and Europe. But the results were disappointing. Observed noise levels turned out to be much higher than the optimistic predictions presented at San Diego. The most sensitive devices constructed in the next two years were produced by Hervé Arditty and his colleagues at Thomson CSF and by a collaborative effort of the University of Hamburg and Telefunken, led by Reinhold Ulrich. They succeeded in reducing noise levels by two to three orders of magnitude, but their devices were still too noisy to measure rotation rates much slower than Earth rate (15°/hour). The primary noise sources appeared to be scattering at mirrors and other interfaces in the system, and coherent Rayleigh backscattering in the optical fibers.

Progress at Stanford and MIT. To deal with these problems, Shaw and his Stanford colleagues, Ralph Bergh and Hervé Lefevre, have now produced a fully integrated single-mode fiber-optic gyroscope. In place of the half-silvered-mirror beam splitters, polarizers and other bulk optical elements that produce undesirable interface scattering, they have developed integrated fiber-optic couplers, polarizers and polarization rotators. In fact, the entire 580-meter fiber-optical path of the Stanford gyroscope (most of it wound on a spool of radius 7 cm) has only a single interface—a splice joining the GaAs laser-diode light source to the rest of the system.

The infrared diode-laser light is split by an integrated coupler into two counter-rotating components that then circle the spool more than a thousand times in opposite directions before returning to the coupler to be reunited and diverted to a silicon photodiode interference detector. Before and after circling the spool, the light passes through an integrated polarizer to insure that one is observing the interference of only a single polarization mode. (This is required to guarantee the identity of the clockwise and counterclockwise optical paths.) A segment of the fiber is bonded to a piezoelectric cylinder that imposes a 174-kHz modulation on the light signal. One determines the rotation-induced Sagnac phase angle by measuring the amplitude of the first harmonic of this modulation signal in the interferometer's output. This gets around the problem that small phase shifts only slightly displaced from an interference maximum are difficult to measure precisely.

Most fibers used in optical communication systems are "multi-mode fibers." That is to say their cores—with diameters on the order of a hundred microns—permit the transit of many spatial modes at a given optical frequency. When one wants to cut off the propagation of higher modes in a microwave guide, one reduces the cross-sectional area of the wave guide. Similarly in fiber optics, if one makes the core small enough, it will transmit only the lowest electromagnetic mode at a particular frequency. With a core diameter of 8 microns, the optical fiber used in the Stanford gyroscope is a "single-mode fiber," transmitting only the lowest mode at the infrared frequency of the diode laser.

It is important to use single-mode fibers in a gyroscope because different modes have effectively different path lengths and propagation velocities. A fiber that supports multiple modes tends to degrade the coherence necessary for a clear Sagnac rotation signal.

Coherent Rayleigh backscattering light off the disordered arrangement of atoms in the fiber is another serious contributor of noise. To reduce this noise, one wants to *weaken* the coherence between backscattered light and the light source. This can be accomplished by reducing the temporal coherence of the source. A solid-state laser diode, with its broader natural bandwidth, is intrinsically less coherent than a gas laser. Thus Shaw and his colleagues found earlier this year that the noise level in their fiber-optic gyroscope fell dramatically when they replaced the original He–Ne laser source with a GaAs diode laser.

With these innovations, the Stanford group reports that they have now achieved a reduction of the rms noise level on the Sagnac phase angle to 1×10^{-6} radians, with measurements averaged over 30 seconds. This gives them a rotation sensitivity of 0.1°/hour—about 10^{-2} of Earth rate. For a given phase noise level, rotation sensitivity increases as the product of the total fiber length and the spool diameter. In the absence of unforseen noise increases coming with increased fiber length, Shaw expects soon to be able to increase the sensitivity of his instrument to the 10^{-3} of Earth rate required for navigation, by winding more turns of optical fiber around the spool and reducing the noise level on the phase angle still further.

Ezekiel and James Davis at MIT, on the other hand, have managed to construct a fiber-optic gyroscope of comparable noise level and rotation sensitivity without for the moment going to the full integration of the Stanford device. The nonintegrated bulk elements of their system include a He–Ne laser, polarizers, mirrors, acousto-optic frequency shifters and an electro-optic phase modulator.

The temporal coherence of the gas laser is artifically degraded by vibrating its mirrors. Rayleigh scattering noise is further reduced by the MIT technique for measuring the Sagnac phase shift. In addition to the phase modulation used at Stanford, the MIT instrument shifts the frequencies of the counter-rotating beams with Bragg-cell acousto-optic frequency shifters until the interference returns to its zero-rotation value. The frequency shift required to get this null reading is then the measure of the rotation rate.

This frequency shifting is done primarily to obtain a calibration-free rotation measurement and to render the Sagnac phase-angle measurement immune to the random intensity fluctuations to which measurements of the first modulation harmonic are sensitive. But it also reduces the noise effect of Rayleigh scattering; the counter-rotating beams are now at slightly different frequencies, raising the frequency of the Rayleigh interference noise to higher frequencies that are largely filtered out. This effect, plus the vibrational broadening of the laser output, also helps get rid of interference noise from scattering at the numerous optical interfaces of the MIT system.

With 200 meters of single-mode fiber wound around a spool of 9.5-cm radius, Davis and Ezekiel report an rms rotation noise level close to 0.1°/hr, also for measurements averaged over 30 seconds. They conclude that this noise level is within a factor of two of their photon noise limit. For measurement integration times, t, up to 30 seconds, their noise does indeed fall like $t^{-1/2}$, as one expects for quantum-limited noise. Ezekiel does not expect, therefore, that full fiber-optic integration will bring his phase-angle noise down much further; but it will provide a more compact instrument. Like the Stanford group, he plans to increase rotation sensitivity by winding more turns of fiber around the spool. One can of course reduce the fractional error introduced by quantum noise by increasing the number of photons—that is to say raising the intensity of the light source.

Work on fiber-optic gyroscopes is also continuing at Thomson CSF, Telefunken and about a dozen other industrial, academic and military laboratories in the US and Europe. Some military applications, for example submarine navigation, will require very high rotation sensitivity and stability, while others, such as "smart bombs," will need less sensitive sensors that are rugged, compact and inexpensive. Ezekiel and Arditty are organizing an "International Conference on Fiber-Optic Rotation Sensors and Related Technologies," to be held next month at MIT.

Sagnac's original work was inspired by his desire to disprove Einstein's special relativity. Now, seven decades later, Ezekiel is planning an experiment to measure the Earth's rotation with high precision by means of the Sagnac effect—essentially to test whether the "fixed stars" provide a good inertial reference frame. —BMS

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Space telescope institute

A ceremony in mid-September marked the start of construction of a building for the Space Telescope Science Institute. Arthur Code (left), professor of astronomy at the University of Wisconsin, was acting director from January until 1 September, when Riccardo Giacconi (right) assumed the directorship. The $8-million, five-story facility is being built on the Homewood campus (Baltimore) of The Johns Hopkins University; it is scheduled for completion in 1983. The 2.4-meter optical telescope (PHYSICS TODAY, March 1981, page 59) is scheduled to be placed in orbit by the Space Shuttle early in 1985. □