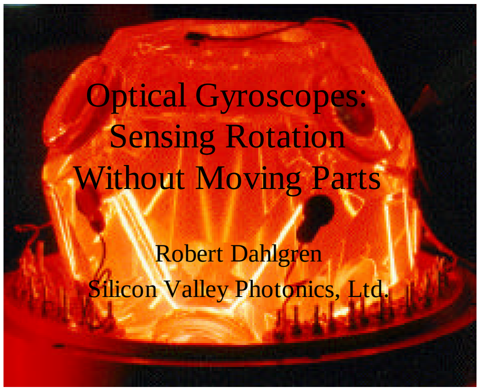


Abstract

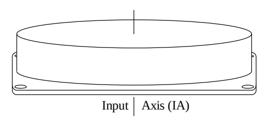
The desire for accurate navigation has been one of the great technology drivers since ancient times. Astronomy, timekeeping, magnetic sensors, the GPS system, MEMs, and spinning-mass gyroscopes are all familiar methods to measure position. The sensing of rotation by optical means was first demonstrated by Sagnac in 1913, and in 1925 Michelson and Gale measured the rotation of the Earth with a 2km loop interferometer. The Sagnac effect was relegated to being a physics curiosity, until the 1960s and the advent of the laser and optical fiber. One of the great achievements of navigation engineering was the harnessing of the Sagnac effect, to make practical and extremely sensitive yet rugged optical rotation sensors. The Sagnac effect is very small, and it is necessary to measure on the order of one part out of 10^{20} to reach high-accuracy requirements. The design and manufacturing of practical optical gyroscopes is a tour-de-force of physics and engineering. Basic concepts such as symmetry, relativity, and reciprocity, and considerable interdisciplinary effort are needed in order to create a design such that every perturbation cancels out except rotation. Optical gyroscopes, and their research and production contracts, were an early driver for many ultra-high-performance optical technologies. Such commonplace items as low-scatter mirrors, ultrasonic machining of glass, lithium niobate integrated optics, polarization-maintaining fiber, superluminescent and narrow-linewidth lasers found their first major applications and customers in these sensors.

Presented to the IEEE SCV LEOS & IMS 5/27/2003.

Outline

- Gyroscope Basics and Applications
- Gyroscope Specifications
- Introduction to the Sagnac effect
- The Ring Laser Gyroscope
- Interferometric Fiber Optic Gyroscope
- Resonant Fiber Optic Gyroscope
- Waveguide Laser Gyroscope
- Micro Optic Gyroscope

Gyroscope Basics

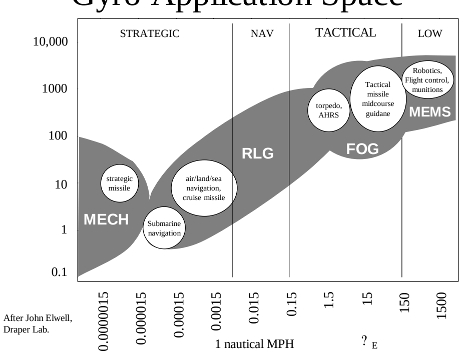


- Rate Gyro: Measures angular velocity ? about IA
- Rate-Integrating Gyro: Measures $\int_0^T ?\ ?t$
- Accelerometer
- Inertial Measurement Unit
  - Three or more Gyros
  - Three or more Accelerometers
  - Signal processing, navigation computer

Types of Gyroscopes

- Spinning-Mass gyroscope
  - Exquisite single and dual-axis versions
  - Generally not a “strapdown” IMU
- Vibratory gyroscope (Coriolis force)
  - Hemispherical, cylindrical, tuning-fork
  - MEMS gyroscope
- Nuclear Magnetic Resonance
- Optical Gyroscope

Gyro Application Space



After John Elwell, Draper Lab.

Important Concepts

- Intertial Frame
  - Absolute reference system
- Reciprocity
  - Replace (t) with (-t) and (x,y,z) with (-x,-y,-z)
- Symmetry
  - Exploited whenever possible
- Special Theory of Relativity
  - Light in vacuum travels at 3?10^8 meters/second
  - Light speed is independent of velocity of source

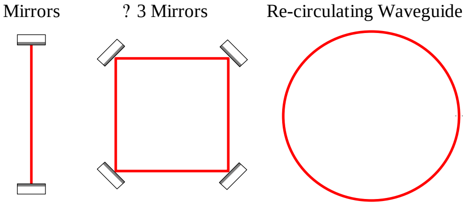
Optical Interferometer

- Classic example of two precisely-aligned mirrors having ideally 100% reflection, separated by L
- Under certain conditions, constructive interference of multiple reflections permits light to pass through
- Transmission only for certain wavelengths ?

  ?/2 = L, ? = L, 3?/2 = L, 2? = L, ...
- Generally: m?/2 = L where m is an integer, and propagation vector perpendicular to mirror coatings
- There will be m "Standing Waves" of size ?/2

Circulation in Interferometers

2 Mirrors ? 3 Mirrors Re-circulating Waveguide



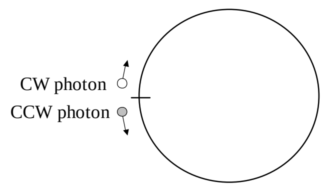
Light Back -and- Forth

Two Independent Beams Circulating Clockwise & Counterclockwise

Two Independent Beams Circulating CW and CCW

CW and CCW light occupy same physical space

Stationary Inertial Frame = Null

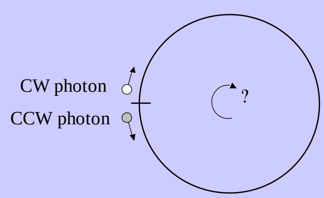


- Both photons experience exactly the same time-of-flight, resulting in destructive interference at the starting point
- $T_{cw} = T_{ccw}$ = 2?R/c where R is the radius
- For optical fiber n ~ 1.5 and T ~ 5 microsecond/kilometer

Rotating Inertial Frame

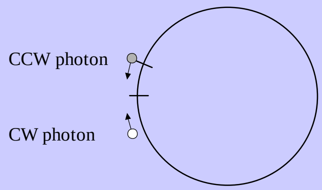
- Consider rotation rate to be ?
  - Units of radians/second, ? > 0 for clockwise
- Rigorous approach requires use of General Relativity, beyond the scope of this talk
- Use a simplified approach
  - Calculate ?L and ?T
  - Refractive index = 1
  - Number of loops = 1

Rotating Inertial Frame



- Both photons start at splice

Rotating Inertial Frame



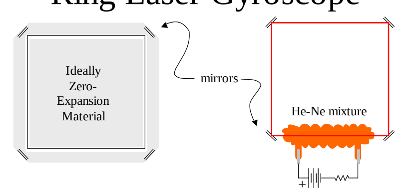
- Both photons start at splice
- Splice point rotated ? T radians, at tangential velocity R?
- L_{cw} = 2?R + R? T_{cw} ≜ cT_{cw}
- L_{ccw} = 2?R – R? T_{ccw} ≜ cT_{ccw}

$$? T ? 2? R ? \frac{1}{? c ? R?} ? \frac{1}{c ? R?} ? ? \frac{4? R^2}{c^2} ? ? \frac{4A}{c^2} ?$$

- Path Length: ? L = c? T = 4A? /c
- Phase shift: ? ? ? = (2?/?)? L = 8?A? /?c
- Phase shift is measured in rotating frame
  - ? can be deduced by measuring ? ? via fringe shift, without knowledge of the absolute reference frame
- Example ? = 633nm, A = 100 cm^2 (L ~ 35 cm)
- Earth's rate $?_e$ = 7.3? 10^{-5} radians/second
  - ? L ~ 9.7 ? 10^{-15} meters - a very small amount
  - ? ? ~ 9.6 ? 10^{-8} radians - just to measure Earth!
  - Need 1000? better than this for navigation.

Ring Laser Gyroscope

Ring Laser Gyroscope

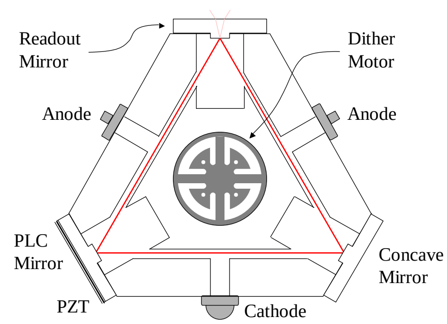


- 3 or more mirrors in a stable alignment
- Sealed and filled with e.g. Helium and Neon
- Electrical discharge excites Helium and Neon ions, producing a population inversion of excited states
- These excited ions provide the gain medium
- With feedback, lasing commences when gain > loss

Ring Laser Gyro Block

Image courtesy SVP

Ring Laser Gyro Schematic

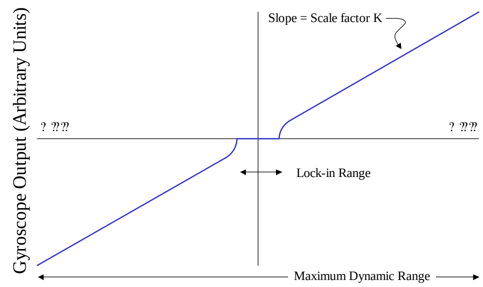


Lasing in a Ring Cavity

- Two lasing beams of light
  - CW and CCW
  - Occupy the same physical space
- Use readout optics to interfere CW and CCW
- If stationary, beams have same wavelength ? (= c/f)
  - Cavity length is the same for both directions
  - Null output when CW and CCW interfere $f_{cw} = f_{ccw}$
- For negligible rotation, beams also have same ?
  - Lock-in effect, due to backscatter (coupled oscillator)
- For rotation above a lock-in rate ? $_L$ f_{cw} ? f_{ccw}
  - Beat frequency is observed ? f = 4A? /? L

Lock-In Effect in Optical Gyros

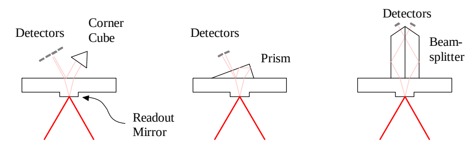
Gyro Output vs. Rotation Rate



Beat Frequencies

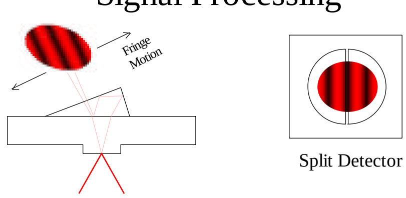
- Several approaches to avoid lock-in
  - Dither motor
  - Magnetic Mirror
- Beat frequency ? f = 4A? /? L
- In terms of phase shift
  - ?? = 2?(? f)t = 8? A? t/? L
- Example ? = 633nm, A = 100 cm^2 (L ~ 35 cm)
  - Optical frequency approximately f = c/? ?? 4.74? 10^{14}
- Earth's rate ? $_e$ = 7.3? 10^{-5} radians/second
  - ? f ~ 13 Hertz
  - ?? ~ 83t radians

RLG Readout Optics



- Unlike other mirrors, the readout mirror is designed to have < 100% reflectivity, along with a slight transmission factor
  - This allows a small fraction of the circulating light to emit
- Attempt to overlay CW and CCW beams
  - Several approaches to achieve stable and robust implementation
- Often uses 2 or more silicon photodetectors
- Followed by low-noise and low-drift electronic preamplification
- Several signal processing approaches to extract ? from ??

Signal Processing

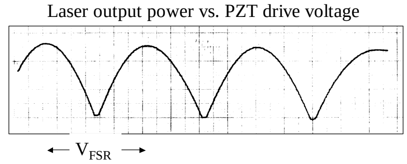


Split Detector

- Fringe counting (1 fringe corresponds to ?? = 2?)
  - Since ? ? ??/t, fringe is ?$_{??}$?? L/4A (5.5 ?-radians for 35cm)
- Fringe counting + sub-fringe interpolation
- Inverse tangent algorithm
- Numerous digital techniques

Path Length Control

Laser output power vs. PZT drive voltage



- Laser power fluctuates as a function of cavity length
- Free Spectral Range FSR = c/nL ~ 860 MHz for 35 cm
- One mirror pistons in and out several microns
- Piezoelectric transducer precisely controls mirror position
- Servo electronics stabilized cavity length

Miniature Ring Laser Gyroscope

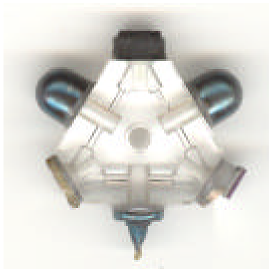
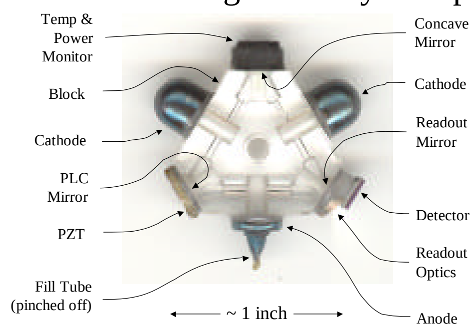
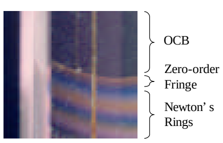


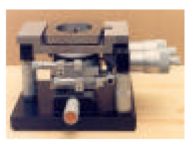
Image courtesy SVP

Miniature Ring Laser Gyroscope



Optical Contact Bonding





- Bonding mirrors to block without adhesive
- Demanding flatness, roughness specifications
- Ultra-clean assembly brings surfaces into contact
  - Newton's rings observed, zero-order fringe is grey
- If conditions are met, a slight pressure initiates bond
  - Van Der Waals force draws surfaces together if d is << 1 micron
- Ageing produces strong, permanent, hermetic seal

Honeywell GG1342 RLG

Image courtesy Honeywell

Multiple Ring Laser Gyroscope

- Possible reduction from nine to six mirrors for 3-axis RLG
- Common block, gas reservoir, and cathode
- Complex machining, but overall parts savings
- Multiple scattering can cause interactions

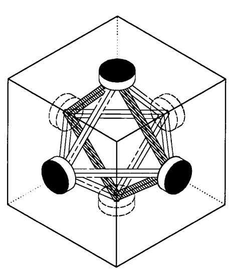
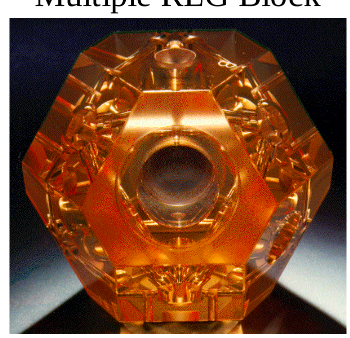


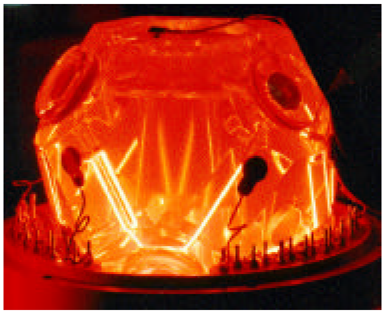
Image courtesy Springer-Verlag © 1993

Multiple RLG Block



Monolithic Ring Laser Gyro (MRLG). Copyright © 2000Kearfott Guidance and Navigation Corporation. Reproduced with permission.

Multiple RLG in Action



Components

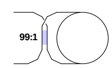
- RLG block
  - Low-expansion material: ULE, Zerodur, or Cervit
  - Filled with proprietary cocktail of He_2 and Ne_2 isotopes
- Mirrors
  - Low scatter is important
  - May have path-length control
- Readout Optics
- Photodetectors
- Dither motor
- Anode/Cathode/Fill tube/Getters

Fiber Optic Gyroscope

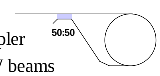
RFOG
IFOG

Fiber Optic Gyroscope

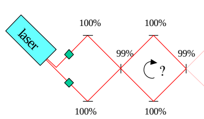
- Resonant Fiber Optic Gyroscope (RFOG)
  - Replace cavity with optical fiber
  - Use high-splitting ratio fiber coupler
  - At resonance, light can circulate
  - Uses narrow-linewidth (coherent) optical sources



- Interferomteric Fiber Optic Gyroscope (IFOG)
  - Longer coil of optical fiber
  - Use 50/50 splitting ratio fiber coupler
  - Topology produces CW and CCW beams
  - Uses broad-linewidth (incoherent) optical source



Passive Optical Gyro



- Resonant Fiber Optic Gyroscope (RFOG)
  - Replace cavity with optical fiber
  - Use high-splitting ratio fiber coupler
  - At resonance, light can circulate
  - Uses narrow-linewidth (coherent) optical sources

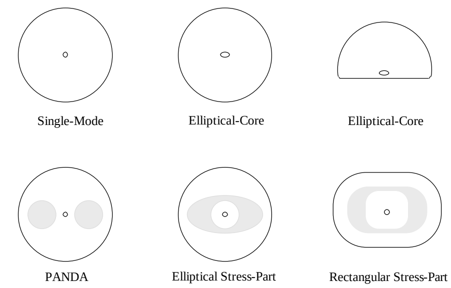
FOG Building Blocks

- Polarization-Maintaining Fiber Coupler
- Fiber polarizer
- PZT Phase modulator
- Fiber depolarizer
- Pigtailed optical isolator
- Planar lightwave circuit
- Optical detectors
- PM optical fiber coil

Polarization-Maintaining Fiber

- "Single-mode" fiber actually propagates 2 modes
  - Two orthogonally polarized modes, e.g. x- and y-mode
  - Ideally travel at the same propagation velocity
  - Small perturbations can cause coupling between x- and y-modes
  - Small perturbations can rotate the local fiber x- and y-axis randomly
- PM fiber has anisotropy to break modal degeneracy
  - One mode has a higher velocity than the other
  - Well-defined principal axes of PM optical fiber
  - X- and y-modes can have many dB of isolation
  - Small, random, perturbations have negligible influence on coupling
- Techniques
  - Elliptical-core optical fiber (3M, D-shaped fiber)
  - Stress-rod fiber (PANDA, Bow-Tie, elliptical cladding)
  - Material (side-pit fiber, photonic bandgap fiber)
  - Need special components, and splicing equipment with axial alignment

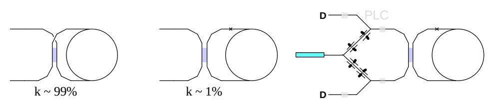
Anisotropy – Breaking Symmetry



Phase and Frequency Shifter

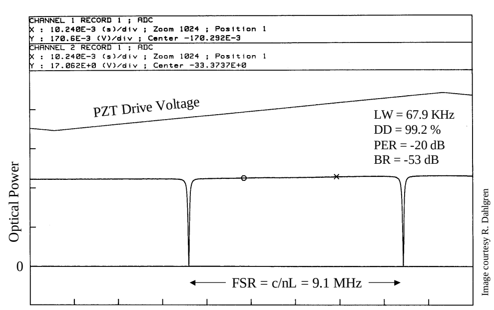
- Fiber-wrapped PZT stretcher
  - Piezoelectric cylinder
- Electro-Optic phase modulator
  - Lithium Niobate PLC
- Acousto-Optic frequency shifter
  - Uses Doppler effect. Difficult to pigtail
- Serrodyne modulator (quasi-frequency shifter)
  - Lithium Niobate PLC phase modulator
  - Driven with sawtooth wave at constant 2?-amplitude
  - Slope of sawtooth = frequency shift
  - High-speed analog electronics needed

RFOG Architectures

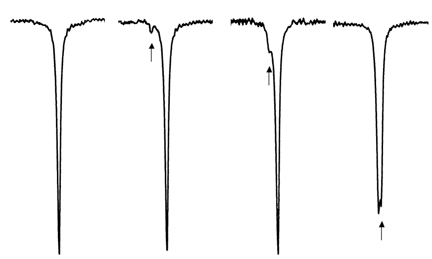


- Resonant Fiber Optic Gyroscope (RFOG)
  - Spliced assembly of low-loss PM fiber coil and PM coupler
  - High-splitting ratio fiber coupler, optimized k = 1-Loss
  - Alternately, low-splitting ratio coupler, set k – Loss
  - Can also add 2nd coupler and operate in transmission mode
- Planar lightwave circuit (PLC)
  - Need electro-optic effect - Ti:$LiNbO_3$ for phase/frequency modulator
  - Descrete or distributed polarizer
  - Splitter with low asymmetry, good polarization performance
  - Pigtailed to PM fiber, packaged to meet aerospace requirements
- Tunable narrow-linewidth source, significant signal processing

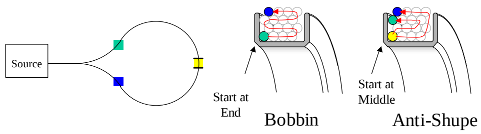
Transmission of RFOG Cavity



Polarization in RFOG Cavity



Coil Winding Style



- For coherent source – only narrow range of coil will suffer parasitic effects due to backscattering
- Exploit symmetry
  - Wind coil from center, alternating layers such that equidistant fibers are physically adjacent
  - Provides immunity to thermal and vibration perturbations that are slow with respect to transit time
  - Called quadropole or anti-Shupe winding pattern

Coil Winding Operation

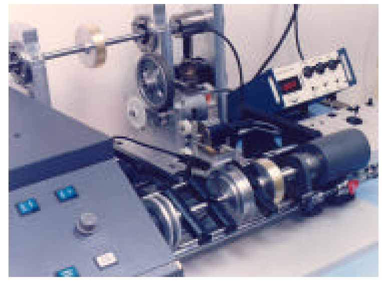


Image courtesy R. Dahlgren

400m Anti-Shupe Coil (unpotted)

Image courtesy R. Dahlgren

Resonant Fiber Gyroscope

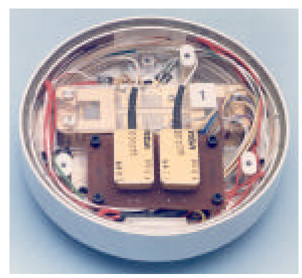


Image courtesy Draper Lab

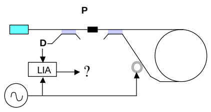
IFOG Architectures

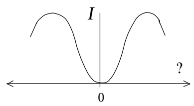
- Minimum-configuration IFOG
  - Uses polarizer (P) and 2nd splitter for detector (D)
  - Sinusoidal phase modulation with PZT fiber stretcher
  - Unbiased operation. At zero rotation $??_? = 0$
  - Open-Loop IFOG operation possible
- 3?3 splitter IFOG (not shown)
- PLC Implementation
  - Needs Ti:LiNbO$_3$ PLC for frequency shifter
  - Phase modulator and one splitter also incorporated
  - Nonreciprocal ?/2 phase shift introduced.
  - At zero rotation, biased at maximum sensitivity point $??_? = ?/2$

Optical Source for IFOG

- Low-coherence source reduces parasitic interference from scattering points and distributed (Rayleigh) scattering
  - Sub-threshold LD
  - Edge-emitting LED
  - Superluminescent Diode
  - Amplified Spontaneous Emission
  - Amplified broadband source
- Can share high-power source between several gyroscopes
- Need to control optical power accurately
- Need to match CW and CCW power to avoid Kerr effect
- Need to control optical center ? accurately

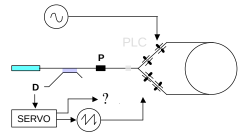
Open Loop Signal Processing

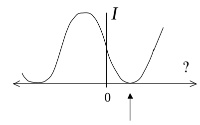




- Open loop
  - Unbiased operation ??$_?$ = 0
  - Minimum sensitivity point for small |?|
  - Sinusoidal oscillator at frequency f_o optimized for transit time
  - Optical phase modulation at optimum amplitude
  - Use lock-in amplifier (LIA) to measure RMS voltage at f_o
  - Use lock-in amplifier (LIA) to measure RMS voltage at $2f_o$
  - Ratio of two RMS voltages yields magnitude and sign of ?
  - Limited dynamic range

Closed Loop Signal Processing





- Closed loop IFOG
  - Needs Ti:$LiNbO_3$ PLC for frequency shifter
  - Phase modulator and one splitter also incorporated
  - Nonreciprocal ?/2 phase shift introduced. At zero rotation ??$_?$ = -?/2
  - Servo-electronics locks operating point to -?/2 maximum sensitivity point
  - Servo-electronics differentially drives frequency shifters to keep on null
  - Servo-electronics yields magnitude and sign of ?
  - Wide dynamic range

Interferometric Fiber Gyroscope

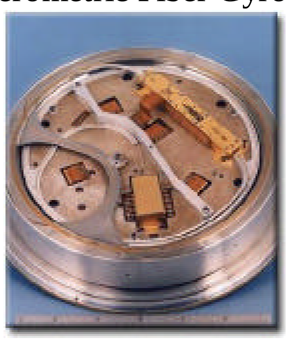


Image courtesy Draper Lab

Interferometric Fiber Gyroscope

Image courtesy Honeywell

Integrated Optic

WLG
MOG
IORS

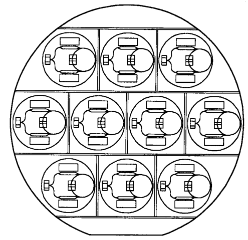
Waveguide Laser Gyroscope

- Integrated optic implementation of RLG
  - Rare-earth doped waveguide ring cavity
  - Pumped at pumping wavelength
  - Mode competition between the two counter-propagating beams prohibit functioning
- Brillouin Effect gyroscope
  - Demonstrated at MIT
- Squeezed-light gyroscope
  - Demonstrated at MIT

Micro-Optic Gyroscope

- Northrop Corp in the 1980s
- Integrated optic implementation of RFOG
  - PLCs have higher attenuation than fiber
  - PLCs had limited length of waveguide
  - Surface acoustic wave (SAW) optical frequency shifters
  - 1-100 degrees/hour performance

Wafer with MOG Chips



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Integrated Optic Rate Sensor

- Rice Systems in the 2000s
- Integrated optic implementation of IFOG
  - Improved PLC technology
  - PLCs had limited length of waveguide
  - Open-loop architectur

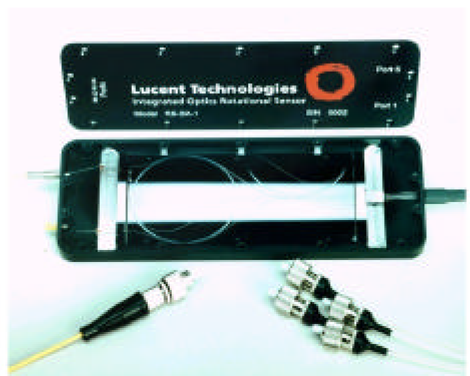

Image courtesy Rice Systems