Quantum Gyroscope

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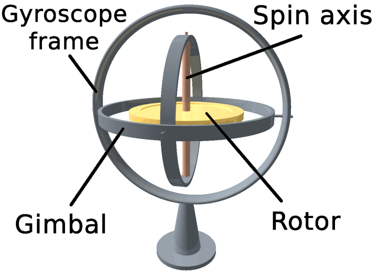
Gyroscope

Gyroscope: a device for measuring or maintaining orientation
Example: Classical Gyroscope



Classical Gyroscope

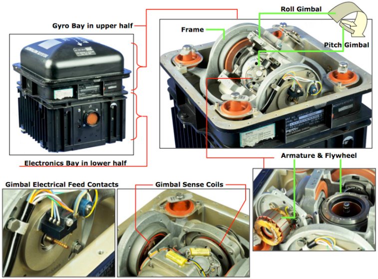
MOVIE: How to work classical gyroscope

Classical Gyroscope

MOVIE: How to work classical gyroscope
Based on the conservation of angular momentum

Classical Gyroscope: airplane sensor

Sperry vertical gyro for Boeing 747 (airplane)



Laser Gyroscope

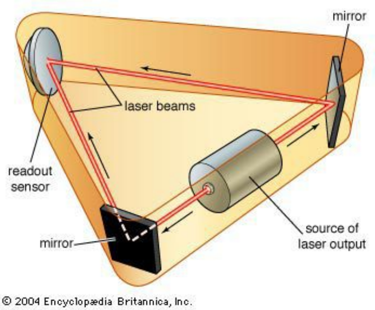


Figure: ring laser gyro (from Encyclopedia Britannica)

Based on the relativity

Laser Gyroscope

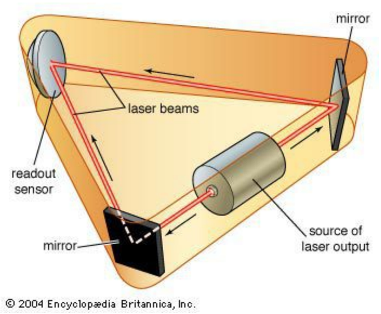


Figure: ring laser gyro (from Encyclopedia Britannica)

Based on the relativity
Used in Boeing 777,787; Airbus A320 330/340,A380 etc.(airplane);
Atlas I/II/III/V, H-IIA/B etc.(rocket)

Laser Gyroscope: Sagnac effect

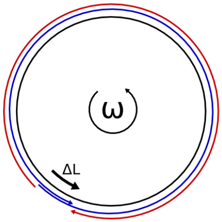


Figure: Light traveling opposite directions

Rotating circular ring

$$R : \text{radius}, \omega : \text{angular velocity}, c : \text{speed of light} \tag{1}$$

A light source emits in both directions from one point on the ring

Laser Gyroscope: Sagnac effect

- Light traveling in the same direction as the rotation
  It needs a catch up time t_1 as

$$t_1 = \frac{2\pi R + \Delta L}{c} \tag{2}$$

ΔL : distance of rotating ring in the interval t_1

$$\Delta L = R\omega t_1 \tag{3}$$

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- Light traveling in the opposite direction as the rotation

$$t_2 = \frac{2\pi R}{c + R\omega} \tag{5}$$

Laser Gyroscope: Sagnac effect

The time difference:

$$\Delta t = t_1 - t_2 = \frac{4\pi R^2 \omega}{c^2 - R^2 \omega^2} \tag{6}$$

Laser Gyroscope: Sagnac effect

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For $R\omega = v \ll c$

$$\Delta t \approx \frac{4\pi R^2 \omega}{c^2} = \frac{4A\omega}{c^2} \tag{7}$$

where $A = \pi R^2$ is the area of the ring.

Laser Gyroscope

How to detect time difference?

Laser Gyroscope

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Interference of the light waves

Laser Gyroscope

How to detect time difference?
Interference of the light waves
phase shift

$$\Delta\phi = \frac{2\pi c \Delta t}{\lambda} \tag{8}$$

λ: wavelength

Laser Gyroscope

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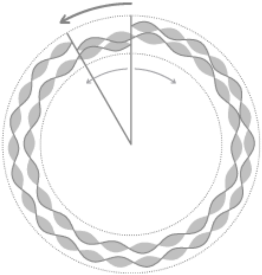

Figure:

Laser Gyroscope: Sagnac effect

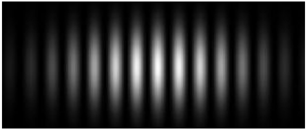

Figure:

For good interference, high quality light source is needed
$\rightarrow$ Laser

Quantum Gyroscope

Using the quantum interference

Quantum Gyroscope

Using the quantum interference
only laboratory at present

- cold neutron (finite lifetime)
- laser cooled atomic gases (nK)
- superfluid He (2.17 K (^{4}He); 2.49 m K (^{3}He))

Short quantum physics; wave-particle duality

- wave behaves as a particle
  - Energy E

$$E = h\nu = \frac{hc}{\lambda} \tag{9}$$

(${h}$:Planck constant, ν: frequency, λ: wave length)

  - momentum p

$$p = \frac{h}{\lambda} \tag{10}$$

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$$\lambda = \frac{h}{p} = \frac{h}{mv} \tag{11}$$

de Broglie theory

Short thermodynamics; Superfluidity

Atoms in the ideal gas (statistical mechanics)
MOVIE: Motion of gas atoms

Short thermodynamics; Superfluidity

Atoms in the ideal gas (statistical mechanics)
MOVIE: Motion of gas atoms
average velocity of atoms

$$\frac{3}{2}k_B T = \frac{1}{2}m\langle \boldsymbol{v}^2 \rangle \tag{12}$$

- k_{B}: Boltzmann constant
- T: temperature

Quantum phase transition

Lowering temperature, average velocity of atoms becomes slowing down.

$\rightarrow$

Wave length of atoms become larger

$\rightarrow$

Quantum interference becomes important at low temperatures

MOVIE: Bose-Einstein Condensation

Quantum phase transition

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$\rightarrow$

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Quantum interference becomes important at low temperatures
MOVIE: Bose-Einstein Condensation
Factors for quantum transitions:

- Temperature
- Density
- Mass of particles
- Fermion or Boson
- Dimensionality (2D or 3D)

Superfluidity

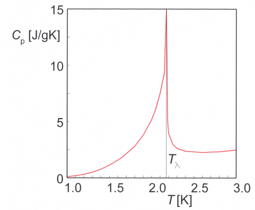

Figure: heat capacity

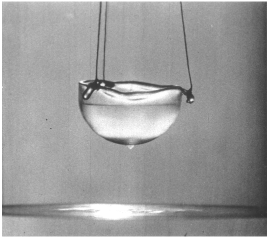

Figure: zero viscosity

Quantum Gyroscope: Superfluid Gyro

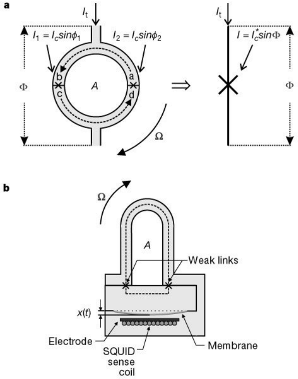

Figure:

R. W. Simmonds, A. Marchenkov, E. Hoskinson, J. C. Davis and R. E. Packard: Nature 412, 55-58 (2001)

Quantum Gyroscope: Superfluid Gyro

Interference pattern

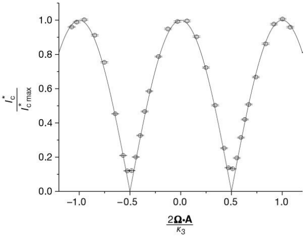

Figure:

Quantum Gyroscope: Superfluid Gyro

Weak Junction

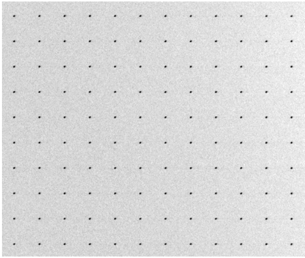

Figure:

S. Narayana and Y. Sato: Phys. Rev. Lett. 106, 055302 (2011)

Quantum Gyroscope: Superfluid Gyro

$$I_c \propto \cos\left(\pi \frac{2\boldsymbol{\Omega} \cdot \boldsymbol{A}}{\kappa_s}\right) \tag{13}$$

- I_c: current
- $\boldsymbol{\Omega}$: Rotation vector
- $\boldsymbol{A}$: Area vector
- $\kappa_s = h/(2m_s)$: quantum of circulation of $^3\mathrm{He}$
- h: Planck constant

Conclusion

Comparison between laser and superfluid gyros

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effective mass of light (frequency ω)

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Superfluid gyro is expected highly sensitve!

Thank you for your attention.