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A new type of optical gyro via electro-optical oscillator

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Abstract

A frequency-sensitive optical gyroscope based on an electro-optical oscillator is proposed. The operating principles of this device are described, its noise and ultimate sensitivity are estimated. The proposed gyroscope is a self-oscillating device whose operating frequency is changed as a result of a change of the rotation rate but it is entirely free from the problem of locking.

All optical gyroscopes based on the Sagnac effect [1] may be classified in two main groups: passive gyros (active medium is placed outside the ring cavity) and active gyros (active medium is placed into the ring cavity)

The passive scheme eliminates the problems associated with having the gain medium inside the interferometer itself. For example, the passive gyro is free from the problem of locking - the main problem of the active gyro.

On the other hand, the active gyro has a large linear dynamic range, and the proportionality constant that relates the beat note of the two beams to the ring's rotation rate (scale factor) is larger in the active gyro then the one that relates the phase shift between the two beams to rotation rate of the ring in the passive gyro.

An additional point to emphasize is the fact that the registration system for the active gyro is much simpler then the one for the passive gyro. For a more detailed review see Ref. [2].

In this paper we propose a frequency-sensitive *quasiactive* gyro, which is entirely free from the problem of locking. Our approach is based on the use of an electro-optical oscillator that is a modulation based amplifier [3] coupled with an optical feedback [4].

The electro-optical oscillator is schematically shown on Fig. 1. The electro-optical frequency shifter 2 (in the simplest case - acousto-optical mod-

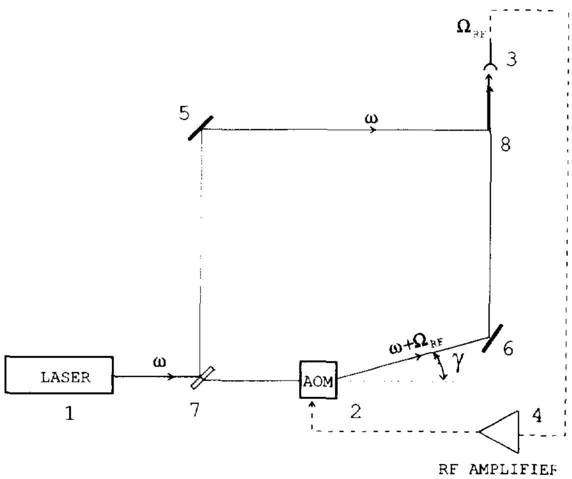

Fig. 1. Schematic of the electro-optical oscillator. 1 - laser, 2 - acousto-optical modulator , 3 - photodetector, 4 - RF amplifier, 5,6 - mirrors, 7,8 - beam splitters.

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ulator [AOM]) converts the light beam from the laser *1* with the frequency ω to the light beam with the frequency $\omega + \Omega_{RF}$. Then this signal beam with the frequency $\omega + \Omega_{RF}$ is mixed with the reference beam of frequency ω on the photodetector *3*. The electrical RF beat signal of frequency Ω_{RF}, after amplification by the RF amplifier *4*, feeds the electro-optical frequency shifter *2*.

It should be noted that whereas the lasing process in a laser is triggered by the spontaneous noise of the active medium, in this generator it is triggered by the shot noise of the photodetector *3*, which results from the Poissonian fluctuations of the reference wave intensity. Therefore, if a laser can be considered a linear amplifier driven by its own spontaneous noise, it is then natural to regard the electro-optical oscillator a modulation based amplifier driven by the shot noise of its own reference beam. It can be stated that the RF amplifier and the frequency shifter partly play the role of the "gain medium" for the electro-optical oscillator.

From the phase balance equation

$$(\omega + \Omega_{RF})\frac{l_s}{c} - \omega\frac{l_r}{c} + \Omega_{RF}(t_{el} + t_{ac}) = 2\pi n, \qquad (1)$$

one may obtain the following equation for the frequency Ω_{RF}:

$$\Omega_{RF} = \omega_{fsr}\left(n + \frac{l_r - l_s}{\lambda}\right) = \omega_{fsr}\left(n + \frac{L}{\lambda}\right), \qquad (2)$$

where $\omega_{fsr} = 2\pi/t_{round}$ is the intermode frequency of the electro-optical oscillator, l_s is the optical path of the signal beam ($2 \to 6 \to 8 \to 3$), l_r is the optical path of the reference beam ($7 \to 5 \to 8 \to 3$ [minus path $7 \to 2$]), $t_{round} = \tau_{ph} + t_{el} + t_{ac}$ is the time of the round trip over the optical part of the signal wave τ_{ph}, electrical part t_{el}, and (in the case of AOM) acoustic part t_{ac} of the signal wave, n is an integer. The experimental observations [4] are in good agreement with Eq. (2).

For a single mode operation, the condition

$$\omega_{fsr} \sim \Delta\Omega_{gain} \qquad (3)$$

must be satisfied. When the AOM acts as an optical frequency shifter and there is no filter in the electrical path, the gain bandwidth $\Delta\Omega_{gain}$ is the bandwidth that deflects the signal beam into the diffraction angle band

$$\Delta\gamma \simeq \frac{\lambda}{d} \qquad (4)$$

near the Bragg angle

$$\gamma = \frac{\lambda}{2\Lambda} = \frac{\lambda}{4\pi v_{ac}}\Omega_{RF}. \qquad (5)$$

Therefore

$$\Delta\Omega_{gain} \simeq 4\pi\frac{v_{ac}}{d}, \qquad (6)$$

where d is the diameter of the laser beam, v_{ac} is the velocity of the acoustic wave.

According to (2), we may have permanent accumulation of the phase difference signal (that is the frequency shift) as a result of any change of the optical path:

$$\Delta\Omega_{RF} = \omega_{fsr}\frac{\Delta L}{\lambda}, \qquad (7)$$

as in active devices.

If we make the reference and signal beams pass through the coil of the optical fiber *9* (see Fig. 2) in opposite directions, the optical path change $\Delta L = 2R\Delta\Omega\tau_{ph}$ will then occur as a result of change of the rotation rate on the value $\Delta\Omega$ and the generating frequency Ω_{RF} changes on the value

$$\Delta\Omega_{RF} = 4\pi\frac{R}{\lambda}\Delta\Omega\frac{\tau_{ph}}{t_{round}} = 4\pi\frac{R}{\lambda}\Delta\Omega\frac{1}{1 + (t_{el} + t_{ac})/\tau_{ph}}, \qquad (8)$$

where $\tau_{ph} = L_{fiber}/c = 2\pi R m_{pass}/c$, m_{pass} is the number of the fiber coil turns, R is the radius of the coil.

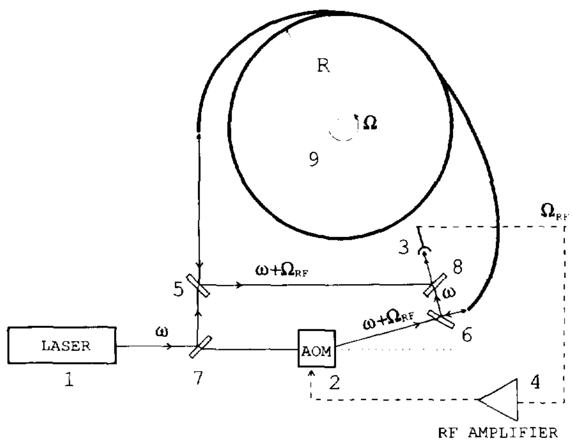

Fig. 2. Schematic of the gyroscope. 1 – laser, 2 – acousto-optical modulator, 3 – photodetector, 4 – RF amplifier, 5,6,7,8 – beam splitters, 9 – coil of the optical fiber.

When τ_{ph} is

$$\tau_{ph} \simeq t_{el} + t_{ac} , \tag{9}$$

then the scale factor of this gyro is half that of active laser gyro. Condition (9) is nearly optimum because any further increase of τ_{ph} entails decrease of the ω_{fsr}, the violation of single mode operation condition (3) (since $\Delta\Omega_{gain}$ always greater then $2\pi/(t_{round} - \tau_{ph})$), and may lead to multimode generation.

One can see that Ω_{RF} is nonzero for zero rotation rate and this gyro has no locking problem. In this respect the proposed gyro is similar to an active laser gyro with null shift. However the null shift is inherent in electro-optical gyro unlike that in the active gyro.

Let us estimate the natural linewidth of the electro-optical oscillator. It is the natural linewidth that will govern the ultimate sensitivity of the device.

Losses in this self-oscillating system exceed the coherent gain by an amount equal to the noncoherent shot noise of the reference wave, and the natural linewidth is $\delta\Omega_{RFnat} = \Omega_{RF}/Q$, where

$$\begin{aligned}\frac{1}{Q} &= \frac{\text{(coherent) energy lost per second}}{\Omega_{RF} \times \text{stored oscillator energy}} \\ &= \frac{\text{shot noise spectral density} \times \Delta\omega_{fsr}}{\Omega_{RF} \times \text{stored oscillator energy}} .\end{aligned} \tag{10}$$

The shot noise spectral density at the photodetector may be found by means of the Schottky formula

$$\langle(\Delta i)^2\rangle \frac{\rho}{\Delta\omega} = 2e\langle i\rangle \frac{\rho}{2\pi} , \tag{11}$$

where ρ is the resistance. The stored oscillator energy at the photodetector is $\langle i^2\rangle \rho t_{round}$, and

$$\langle i\rangle = \frac{\eta e}{\hbar\omega}\sqrt{2P_s P_r} , \tag{12}$$

where P_s and P_r is the signal and reference light beam power at the photodetector, η is the photodetector quantum efficiency, $\hbar$ is Plank's constant. So the natural linewidth of the electro-optical oscillator is

$$\delta\Omega_{RFnat} \simeq \frac{\hbar\omega}{\eta P t_{round}^2} , \tag{13}$$

where P is the total light power at the photodetector.

For the measurement time $t_m \ll 1/\Omega_{RFnat}$, the minimum detectable frequency change is

$$\delta\Omega_{RFmin} \simeq \frac{1}{t_{round}}\sqrt{\frac{\hbar\omega}{\eta P t_m}} . \tag{14}$$

Considering that $\tau_{ph} = 2\pi R m_{pass}/c$, we have from (8) and (14) the minimum detectable change of the angular velocity of the ring to be

$$\delta\Omega \simeq \frac{\omega}{2(2\pi)^3}\frac{\lambda^2}{R^2}\frac{1}{m_{pass}}\sqrt{\frac{\hbar\omega}{\eta P t_m}} . \tag{15}$$

For comparison, in an active laser gyro the rotation of the ring laser cavity leads to a frequency difference between the counterpropagating waves. This difference is

$$\Delta\omega = 4\pi\frac{R}{\lambda}\Omega . \tag{16}$$

The minimum detectable change of the laser frequency is determined by the well-known Schawlow-Townes equation [5]

$$D = \delta\omega_{spont} = \frac{\hbar\omega}{P\tau_{ph}^2} , \tag{17}$$

and for the measurement time $t_m \ll 1/D$, is

$$\delta\omega_{min} \simeq \frac{\delta\varphi_{spont}}{t_m} = \sqrt{\frac{D}{t_m}} = \frac{1}{\tau_{ph}}\sqrt{\frac{\hbar\omega}{P t_m}} , \tag{18}$$

and from (16) and (18), considering that $\tau_{ph} = 2\pi R m_{pass}/c$ (here m_{pass} is the number of the photon passages in the cavity, which is $\sim 1/(1-r)$, r the reflection of the cavity's mirrors), we have

$$\Omega_{active} \simeq \frac{\omega}{2(2\pi)^3}\frac{\lambda^2}{R^2}\frac{1}{m_{pass}}\sqrt{\frac{\hbar\omega}{P t_m}} . \tag{19}$$

The sensitivity of a passive gyro is limited by the shot noise. The phase difference arising from the rotation of the ring cavity or the optical fiber coil with the angular velocity Ω

$$\Delta\varphi = 2\pi\frac{\Delta L}{\lambda} = 16\pi^3\frac{\Omega}{\omega}\frac{R^2}{\lambda^2}m_{pass} \tag{20}$$

must be larger than the quantum uncertainty of the phase of light in the coherent state

$$\delta\varphi_{shot\ noise} \simeq \frac{1}{\sqrt{n}} = \sqrt{\frac{\hbar\omega}{\eta P t_m}}, \tag{21}$$

where n is the number of photoelectrons at the photodetector during the measurement time t_m.

As a result the ultimate sensitivity of the passive gyro is

$$\Omega_{\text{passive}} \simeq \frac{\omega}{2(2\pi)^3} \frac{\lambda^2}{R^2} \frac{1}{m_{\text{pass}}} \sqrt{\frac{\hbar\omega}{\eta P t_{\text{m}}}} . \tag{22}$$

It is worthy to notice that in the passive resonator gyro [6] the minimum detectable frequency change $\delta\omega_{\min}$ is determined by the Poissonian fluctuations of the intensity of the laser light passing through the external cavity with linewidth $\delta\omega_{\text{cav}}$:

$$\delta\omega_{\min} \simeq \frac{\delta\omega_{\text{cav}}}{\sqrt{n}} = \frac{1}{\tau_{\text{ph}}} \sqrt{\frac{\hbar\omega}{\eta P t_{\text{m}}}} , \tag{23}$$

which nearly coincides with (18), and the ultimate sensitivity is again:

$$\Omega_{\text{passive}} \simeq \frac{\omega}{2(2\pi)^3} \frac{\lambda^2}{R^2} \frac{1}{m_{\text{pass}}} \sqrt{\frac{\hbar\omega}{\eta P t_{\text{m}}}} . \tag{24}$$

The fact that the passive resonator gyro has approximately the same rotation sensitivity as the traditional passive gyro was pointed in Ref. [7].

So the ultimate sensitivity (15, 19, 22, 24) is approximately the same for all types of gyro (the factor η plays a secondary role).

For standard gyro parameters ($P \sim 1$ mW, $t_{\text{round}} \sim 1$ μs, $t_{\text{m}} \sim 1$ s) the oscillator natural linewidth defined by (14) is $\sim 10^{-2}$ Hz. There are two main obstacles to the reaching such an oscillator frequency stability: fluctuations of the pump laser frequency and mechanical instabilities of the optical components of the oscillator.

It is seen from Eq. (2) that the laser frequency fluctuations have but a little influence on the oscillator frequency Ω_{RF} when the optical path difference $L = l_{\text{r}} - l_{\text{s}}$ is about zero. One can say that the oscillator frequency follows the laser frequency fluctuations with a factor $L/(t_{\text{round}}c)$. For example if L is ~ 3 cm (and $t_{\text{round}} \sim 1$ μs) then this factor is $\sim 10^{-4}$ and pump laser linewidth must be less then ~ 100 Hz to reach the oscillator stability determined by (14). To reach such a narrow pump laser linewidth, use can be made of an external laser frequency stabilizer based on the electro-optical oscillator [4].

To reduce a noise associated with the mechanical instabilities of the optical components, it seems very promising to design the electro-optical gyro as an all-fiber device.

In conclusion it is worthwhile to compare the gyro proposed with passive frequency-sensitive gyros [6,8]. In the passive resonator gyro [6], negative feedback servo-systems adjust laser frequencies to the clockwise (CW) and counterclockwise (CCW) resonant frequencies of an external ring resonator. In the frequency-sensitive fiber gyro [8], the negative feedback servo-system changes the frequency of the CW or CCW light beam to compensate the phase shift due to rotation of the fiber coil. Unlike these *passive* frequency-sensitive devices requiring at least *two* frequency shifters and complicated feedback servo-systems, the proposed gyro (with *one* frequency shifter) is a *self-oscillating* device that changes its own frequency in response to the change of the rotation rate. Since the RF amplifier and frequency shifter in the electro-optical oscillator partly play the role of an active medium, the proposed device may be called *quasiactive gyro*.

To summarize, we have proposed a self-oscillating frequency-sensitive optical gyroscope without any laser medium inside the ring, which is free from the problem of locking and whose scale factor can be approximately the same as for the laser gyro. The ultimate sensitivity of the gyro proposed nearly the same as that of the traditional passive and active gyros.

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