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New hybrid integrated resonant optical gyroscope

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Abstract: A new hybrid integrated resonant optical gyroscope was presented. All the passive optical elements were fabricated on a single silicon substrate. The active part, which concludes only the laser and photodetectors, was mounted to the waveguide with flip-flop process. The main advantage of the construction was removing the external modulator, and it brings the integration to a new level. For the proposed hybrid integrated optical gyro, an alternative modulation/demodulation method was described in detail. High frequency square waveform modulation wave was assigned to the injection current port of the laser to obtain the frequency modulation. When the gyro rotates, the resonator curve of the two directions departs, resulting in square-wave output, which can be detected to obtain the angular velocity. This work has a big contribution to the integrated optical gyro system.

Key words: integrated optical gyro;　hybrid integration;　current modulation

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新型混合式集成光学陀螺系统

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摘　要：提出了一种混合式集成光学陀螺系统结构。所有的无源光学器件在单一硅片上进行加工。光源和探测器等有源器件通过倒装焊的工艺进行键合。此种结构的主要优势是去除了外部的调制器，将陀螺系统的集成化提高到一个新水平。详细阐述了混合式集成光学陀螺的调制解调技术。系统的频率调节通过在激光器的输入电流上加载高频方波来实现。当陀螺旋转时，谐振腔内传输的两路光分离，输出呈方波形式，通过检测方波信号可以得到角速度的值。该研究对集成光学陀螺系统的研究有较大贡献。

关键词：集成光学陀螺；　混合集成；　电流调制

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0 Intruduction

Gyroscope is a key element used in navigation system. With the development of micro/nano fabrication technology, the miniaturization and integration of the gyro system has been widely studied[1]. There are two kinds of integrated gyro system, the micro-electromechanical system (MEMS) gyro and the integrated resonant optical gyro (IROG)[2]. The MEMS gyro has captured many rate-gyro applications because of small size and low cost, however it lacks the precision and dynamic performance needed for stabilization and navigation applications. In addition, the MEMS gyro is susceptible to instantaneous shock and vibration errors, which will further degrade its performance. The IROG, which has excellent advantages regarding its compactness, stability, reliability, and eases of fabrication, has become one of the most promising candidates for next-generation inertial rotation sensors.

The IROG technology has been widely investigated since the beginning of the last decade[3-7]. Most of them are complicated system, which include fiber laser or semiconductor laser, photodetector, frequency or phase modulator, and waveguide resonator. All the elements are connected with fiber, which makes the system lower level of integration. The acoustooptic modulator uses amorphous or multicrystal films to realize frequency shifting, and the phase modulator is fabricated by $LiNbO_3$ crystal, both the two kinds material are difficult to be integrated with the silica waveguide resonator, which becomes the main critical obstacle for the integration. The silicon waveguide modulator, which would be well compatible with silica resonator, has been developed widely, and the modulator with halfwave voltage of 1 V and bandwidth of 60 GHz has been researched. However, the silicon modulators are based upon free carrier electrooptic effects, and the real refractive index variation is nonlinear with the voltage, which is difficult to get the quantitative frequency shift by phase modulation. Above all, the absorption coefficient of silicon waveguide is changed with the real refractive index, which would bring extra loss into the gyro system.

For the disadvantage of integration of modulator, this paper proposed a new hybrid integrated optical gyro system. The external modulator is removed, and the modulation/demodulation technology is realized by the current change of the semiconductor laser. In this integrated construction, all the passive optical circuit is fabricated on the silica waveguide, and the laser and photodetector are integrated by flip-flop mounting procedure. The presented structure has made a big contribution to the integration of the resonant gyro system.

1 Optical structure of hybrid IROG

The schematic diagram of the resonant optical gyro with external modulator is shown in Fig.1(a), which includes the laser, photodetectors, modulator, and waveguide resonator, all are connected with fiber. Fig.1(b) shows the schematic diagram of the proposed hybrid integrated optical gyro. All the elements are

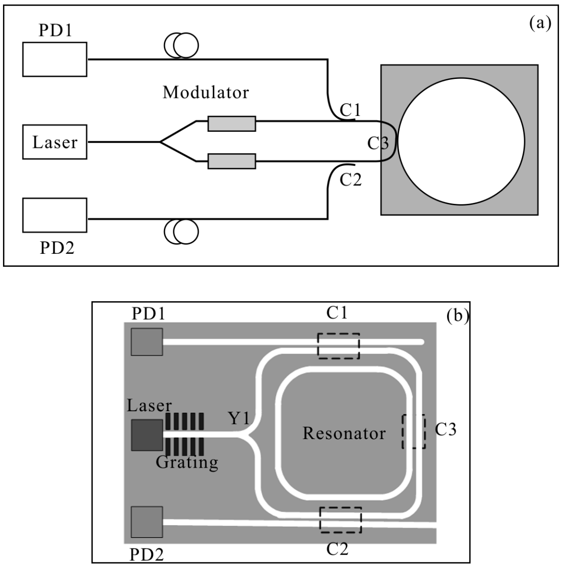

Fig.1 Schematic diagram of resonant optical gyro with external modulator and schematic diagram of hybrid integrated resonant optical gyro

integrated on a single silicon chip. The passive parts, which conclude one resonator, three directional couplers, one Y-branch coupler and the grating filter, are firstly fabricated on the silica waveguide. Then the laser and photodetectors are picked up and placed on the mounting pedestals fabricated on the substrate. The unmounted laser had to be powered on during the active alignment process. Comparing with the system in Fig.1(a), the obvious advantage is removing the external modulator. So that, all the optical parts except the laser and photodetectors are fabricated to be the same size silica waveguide, which makes the transmitting loss much lower and realizes higher signal-to-noise ratio (SNR) of the gyro. Otherwise, the exclusion of the fabrication procedure of the modulator makes the gyro system easy to be fabricated.

The hybrid IROG system has the same working principle with the normal resonant optical gyro. Lightwave from the laser is equally divided by the Y-branch and launched into resonator through the coupler C3, where one lightwave travels clockwise (CW), and the other one counter-clockwise (CCW), respectively. Then the CW and CCW lightwaves travel out of the resonator through the couplers C2 and C1, eventually sensed in reflection mode by the InGaAs PIN photodetectors PD1 and PD2.

The resonant frequency difference Δf between the CW and the CCW beams propagating in the optical ring resonator according to the Sagnac effect is given by[4]:

$$\Delta f=\frac{4A}{n_{\mathrm{eff}}\lambda L}\Omega \tag{1}$$

where A is the area enclosed by the resonator; L is the optical perimeter; n_{eff} is the waveguide refractive index; λ is the wavelength of the light and Ω is the rotation rate. Note that Δf is independent of the number of turns in the waveguide resonator.

As can be seen from Eq.(1), the Δf is proportional with Ω. So that the rotation rate can be obtained by detecting the frequency difference.

2 Signal modulation technique for hybrid IROG

The hybrid IROG system shown in Fig.1 (b) has no external modulator, and the signal modulation technique is realized on changing the current of the laser.

The schematic illustration of the signal detection for hybrid IROG is shown in Fig.2. The laser is driven by square waveform from laser driver circuit to modulate the lightwave frequency in order to achieve high sensitivity. The output of the PD1 is fed back through the lock-in amplifier 1(LIA1) and the feedback circuit (FBC), and then the frequency of the laser is controlled by the output from FBC through the laser driving circuit module and locked to the CCW resonance frequency f_{ccw}. At the same time, the demodulated signal from the lock-in amplifier 2 (LIA2) provides a gyro output which is proportional to the rotation rate of the hybrid IROG. The signal detection technique is very important to the hybrid RIOG system because the ultimate sensitivity of the gyroscope is determined by the detection precision. The signal processing scheme, as shown in Fig.2, is designed to realize the signal modulation, demodulation, closed-loop control, and detection of the angular velocity.

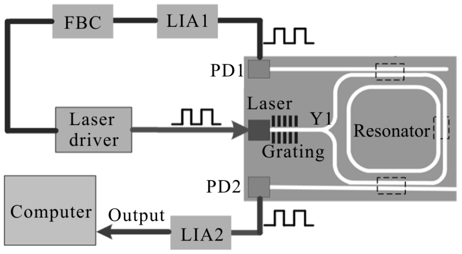

Fig.2 Schematic illustration of signal detection for hybrid IROG

Considering the temporal coherence of the laser, the resonance curve of a ring resonator is expressed as[8]

$$T_{\mathrm{frr}}=\frac{I_{\mathrm{out}}}{I_{\mathrm{in}}}=T_2-\frac{2TR\cos(2\pi\tau f)-M}{1+Q^2-2Q\cos(2\pi\tau f)} \tag{2}$$

where

$$M=2RTQ+\frac{(R')^2}{1-(Q')^2}(1-Q^2) \tag{3}$$

$$\begin{cases} R'=\sqrt{(1-\kappa)(1-\alpha_c)} \\ R'=\kappa(1-\alpha_c)\sqrt{(1-\alpha_L)} \\ Q'=\sqrt{(1-\alpha_L)(1-\kappa)(1-\alpha_c)} \\ R=R'\exp(-\pi\Delta f_0\tau) \\ Q=Q'\exp(-\pi\Delta f_0\tau) \end{cases} \tag{4}$$

where α_c and α_L are the loss of the resonator coupler and the resonator, respectively; Δf_0 is the spectral linewidth of the laser; f is the input light frequency and τ is the optical transmission time in the ring expressed as $\tau=n_{\rm eff}\cdot L/c$. Here c is the velocity of light.

Transfer function expressed by Eq.(2) has been plotted (Fig.3(a)) with parameters in Tab.1. As it can be seen from Fig.3 (a), $\Delta T_{\rm frr}$ is different for the same Δf at different working frequency and it is almost proportional to the slope of resonance curve. In hybrid IROG, high performance corresponds to high signal-to-noise ratio (SNR), which demands larger $\Delta T_{\rm frr}$ when $I_{\rm in}$ is fixed. Therefore, it is necessary to shift the frequency to the maximum slope point of resonance curve in order to obtain the largest $\Delta T_{\rm frr}$.

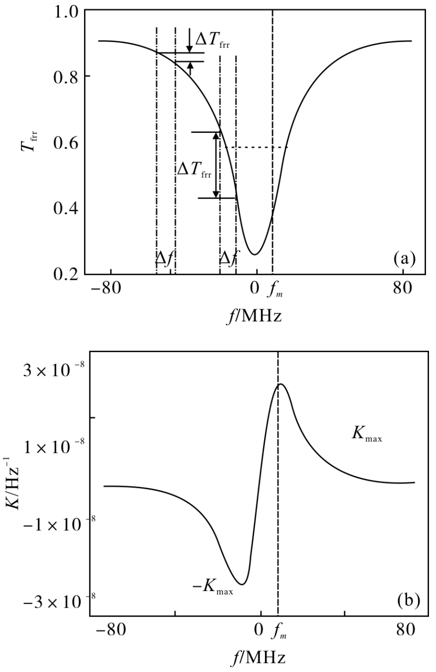

Fig.3 Resonance curve of resonator with parameters of Tab.1 and slope of resonance curve

Tab.1 Parameters for silica waveguide resonator

Characteristics	Varies	Values
Wavelength of light/μm	λ	1.55
Linewidth of laser/kHz	Δf_0	30
Refractive index	$n_{\rm eff}$	1.46
Transmitting loss per unit length/dB·cm^{-1}	α	0.01
Inserting loss of coupler/dB	α_c	0.3
Ring diameter/m	D	0.04
Cross port coupling coefficient	κ	0.03

The slope K of the resonance curve by fitting Eq.(5) (n=1,2,3…) is shown in Fig.3 (b), whose absolute value is symmetrically distributed as the resonance curve. f_m is the frequency shift corresponding to maximum K.

$$K=\frac{{\rm d}T_{\rm frr}}{{\rm d}f}\Big|_{f_n}=\frac{T_{\rm frr}(f_n)-T_{\rm frr}(f_{n-1})}{f_n-f_{n-1}}=\frac{M-2TR\cos(2\pi\tau f_n)}{1+Q^2-2Q\cos(2\pi\tau f_n)}-\frac{M-2TR\cos(2\pi\tau f_{n-1})}{1+Q^2-2Q\cos(2\pi\tau f_{n-1})}\Big/(f_n-f_{n-1}) \tag{5}$$

$$f_m=f|_{K=K_{\max}} \tag{6}$$

Figure 4 shows the current modulation technique of the hybrid IROG. A high frequency square waveform modulation wave is assigned to the injection current port of the laser to obtain the frequency modulation. The up half period and the down half period of the square waveform can realize frequency shift of f_m and $-f_m$, respectively, which are also the frequency change of the laser output. When the

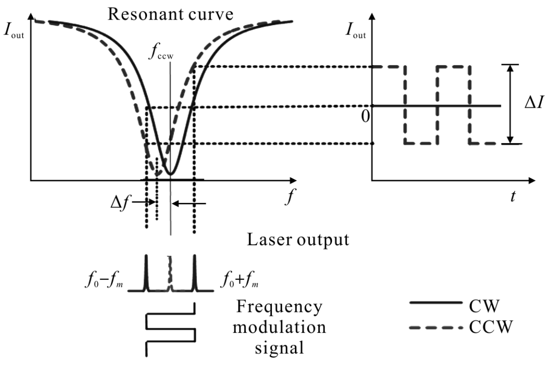

Fig.4 Current modulation technique of hybrid IROG

average frequency of the laser is equal to the resonance frequency of the resonator, it produces DC output. When the average frequency deviates from the resonance frequency of the resonator, the output intensity in the up half period is no longer identical to that in the down half period, but as a square waveform whose amplitude would be feedback to modulate the average frequency of the laser to be the resonator frequency.

When the average frequency of laser is locked to the frequency of CCW curve, the output of PD2 would present the frequency shift Δf of CW. When the gyro is stable, $\Delta f=0$, the modulated lights with frequencies of $\Delta f-f_m$ and $\Delta f+f_m$ are symmetrically settled on two sides of the resonant curve, in which case $\Delta I=0$. When the gyro rotates, CW departs from CCW, resulting in modulated lights′ frequencies asymmetric on resonant curve and square −wave output, in which case ΔI can be expressed exactly as in Eq.(7) by considering Eq.(2), where the symbol "±" are decided by rotating direction. So that the rotate rate can be obtained by detecting the value of ΔI.

$$\Delta I=\pm I_0(T_{\mathrm{frr}}|_{\Delta f-f_m}-T_{\mathrm{frr}}|_{\Delta f+f_m})=$$

$$\pm I_0\left(\frac{2TR\cos[2\pi\tau(\Delta f+f_m)]+M}{1+Q^2-2Q\cos[2\pi\tau(\Delta f+f_m)]}\right)-\left(\frac{2TR\cos[2\pi\tau(\Delta f-f_m)]+M}{1+Q^2-2Q\cos[2\pi\tau(\Delta f-f_m)]}\right) \tag{7}$$

For the current modulation technique, the frequency shifts as the current of the laser changed, which obviously produces an accompanying amplitude modulation. The intensity fluctuation would lead to the attenuation distortion of the resonance valley. Although a subtraction circuit is adopted to resolve the problem[9], the procedure is not a closed loop system, which is sensitive to temperature disturbance. So that, the lasers with constant output intensity when frequency modulation should be developed to satisfy the new hybrid IROG system.

3 Conclusions

In this paper, a new hybrid integrated resonant optical gyro is presented. The external modulator is removed, which contributes much to the integration of gyro system. All the passive elements are fabricated on a single silicon substrate. The active parts, laser and photodetectors, are mounted to the waveguide with flip −flop process. For the proposed gyro system, current modulation technical is adopted to realize frequency shift. This is for the first time to realize so high level integration, which has a big contribution to the integrated optical gyro system.

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