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Integrated optical gyroscope using active Long-range surface plasmon-polariton waveguide resonator

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Optical gyroscopes with high sensitivity are important rotation sensors for inertial navigation systems. Here, we present the concept of integrated resonant optical gyroscope constructed by active long-range surface plasmon-polariton (LRSP) waveguide resonator. In this gyroscope, LRSP waveguide doped gain medium is pumped to compensate the propagation loss, which has lower pump noise than that of conventional optical waveguide. Peculiar properties of single-polarization of LRSP waveguide have been found to significantly reduce the polarization error. The metal layer of LRSP waveguide is electro-optical multiplexed for suppression of reciprocal noises. It shows a limited sensitivity of $\sim 10^{-4}$ deg/h, and a maximum zero drift which is 4 orders of magnitude lower than that constructed by conventional single-mode waveguide.

Optical gyroscopes including interferometric optical gyroscope (IOG) and resonant optical gyroscope (ROG) are high-performance rotation sensors based on Sagnac effect for inertial navigation system. Compared with engineered interferometric fiber optical gyroscopes^{1,2} and laser gyroscopes³, ROGs constructed by planar optical waveguide ring resonator are promising rotation sensors with advantages of high sensitivity, all solid-state and integration, which are research focus in inertial navigation field recently^{4,5}.

The intrinsic drawbacks of the conventional optical waveguide such as high propagation loss and polarization crosstalk^{6,7} significantly restrict the further improvement of ROG's sensitivity. In order to solve this problem, ROG constructed by active optical waveguide ring resonator have been presented to reduce the propagation loss⁸. However, the pump noises which are dependent mainly on the pump strategy and the mode characteristics of the active optical waveguides may simultaneously degenerate the gyroscope's sensitivity. On the other hand, the low polarization extinction ratio of optical waveguide has a potent effect on the gyroscope's performance⁹. To overcome the above bottlenecks of ROG based on optical waveguide, a novel propagation medium with characteristics of low propagation loss and high polarization extinction ratio is needed. The new research LRSP waveguide is the very medium which supports a mixed mode of electrons and photons with long propagation distance. Numerous studies have shown that LRSP waveguide supports optical surface waves propagating along a metal-dielectric interface¹⁰⁻¹³, which just has peculiar properties of single-polarization (TM) with high polarization extinction ratio¹⁴ and propagation loss compensation with low pump noises^{15,16}. In addition, electro-optical multiplexing is a peculiar property of LRSP waveguide that the metal layer can act both as heating electrode and waveguide element simultaneously¹⁷.

In this paper, we first propose an ROG using an active LRSP waveguide ring resonator as the sensing element, which has superior characteristics of high sensitivity, low polarization error, and suppressing reciprocal noises by thermo-optical modulation of the LRSP ring resonator. This gyroscope may be promising to become the new generation monolithically integrated optical gyroscope.

Results

We show the configuration of the present ROG using active LRSP waveguide resonator in Fig. 1. The LRSP waveguide resonator with gain medium is pumped under a vertical pumping source with wavelength of 982 nm shown as the inset of Fig. 1 to compensate the propagation loss. The LRSP waveguide consists of Si substrate,

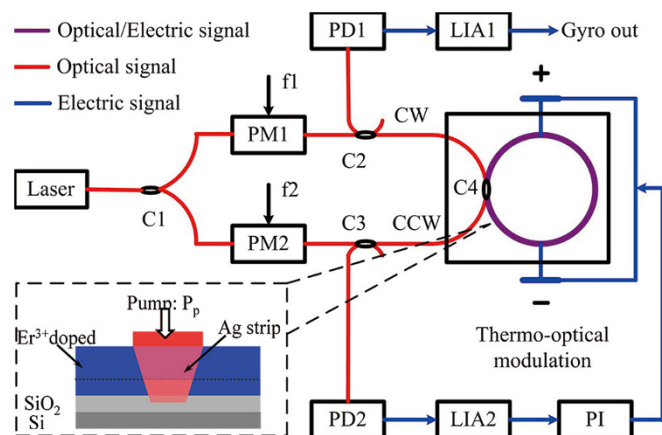


Figure 1 | Schematic diagram of the ROG using active LRSPP waveguide ring resonator. Inset shows the cross-section of the active LRSPP waveguide ring resonator.

silver strip, and Erbium-doped phosphate glass. The Erbium-doped glass could be fabricated with 4.2% Er_2O_3 and 1% Yb_2O_3 ¹⁸. It should be noted that, although the vertical pumping strategy used for the present LRSPP active waveguides is the same as conventional optical waveguide¹⁹, it has more advantages and technology superiorities^{16,20} which will be discussed in following discussion section.

We firstly deduced the expression of the shot noise limited sensitivity (SNLS) and the spontaneous emission limited sensitivity (SELS) shown as Eq. (1) and (2), respectively. (See supporting information for details)

$$\Delta\Omega_{snls} \cong \left(\frac{\lambda_a L}{4A} \right) \frac{\sqrt{2}\Delta f_{FWHM}}{\sqrt{\frac{\eta_D \tau_D P_{in}}{hf_a} \times \frac{T_{max} - T_{min}}{\sqrt{T_{max}}}}} \quad (1)$$

$$\Delta\Omega_{sels} \cong \frac{\lambda_a c}{4\sqrt{2}\pi AN_{eff}} \left[\frac{\alpha_{intr} L h f_a}{FP_{in} \tau_D} \right]^{1/2} \quad (2)$$

where Δf_{FWHM} is the full width of half maximum (FWHM) of the resonant peak of the resonator, F is the finesse of the resonator. The net loss α_{net} and intrinsic loss α_{intr} represent the propagation loss of the LRSPP waveguide of the ring resonator with gain and without gain, respectively. The physical meanings of the other parameters in Eq. (1) and (2) are shown as the supporting information.

Then, we investigated the sensing sensitivity of the LRSPP waveguide ROG decided by the loss compensation strategy. In the calculation, we set the parameters as follows. The radius r of the ring resonator is 2 cm, the width and thickness of silver film are 6 μm and 11 nm respectively, the laser power is 1 mW, the quantum efficiency and integration time of the photo detector are 0.9 and 1 h (large integration time is usually considered in high sensitivity gyroscope applications³), respectively. By numerically solving the model using the finite element method²¹, we obtained that the effective mode index is 1.4511 and the propagation loss of the LRSPP waveguide is 0.14 dB/cm. As a vertical pumping mechanism is used, the total enhancement of signal SPP tends to be linear. For loss compensation, the total loss of LRSPP waveguide is 1.76 dB and the required pumping power should be ~ 100 mW¹⁸. Fig. 2 shows SNLS (upper) and SELS (lower) determined by the power coupling ratio k of the coupler C4 and net loss of the curved waveguide. Here k represents the fraction of power coupled into the ring cavity from the input port of the directional coupler C4, as defined in Ref. 8. With an increasing k , SNLS and SELS vary with different trends. In order to achieve a higher sensitivity, we constructed LRSPP waveguide gyroscope with multi-turn resonator, whose structure is coincide with Ref. 22. Fig. 3 (b)

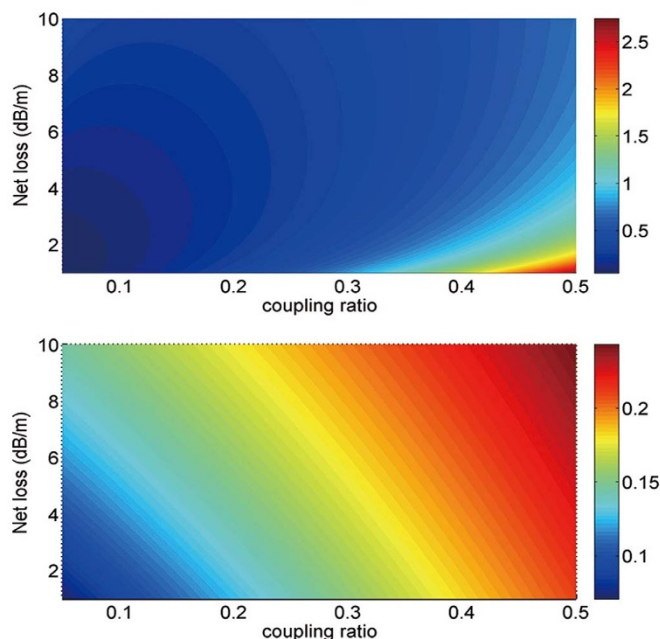


Figure 2 | SNLS (upper) and SELS (lower) decided by coupling ratio k and net loss.

shows the sensitivity dependent on the number of turns of resonator N_{turn} . Fig. 3 (b), (c) and (d) show the relations between the min value of coupling ratio k_{min} and sensitivity. N_{turn} and k_{min} has big influence on the gyroscope's sensitivity.

The LRSPP waveguide ROG has advantages of high sensitivity as well as low maximum zero drift caused by polarization mismatch of the input light which shows the influence of state of polarization on the ROG's performance⁹. Fig. 4 (a)–(c) show the maximum zero drift Ω_{pm} of ROG by using single-mode optical waveguide, polarization maintaining optical waveguide and LRSPP waveguide with different N_{turn} . The Ω_{pm} of LRSPP waveguide ROG is 1.47×10^{-3} deg/h when $N_{turn} = 8$. Fig. 4 (d)–(f) show the Ω_{pm} of LRSPP waveguide ROG with different resonator radiuses and turns, which indicate that the value of Ω_{pm} decreases rapidly as r or N_{turn} increases.

The other notable property of the LRSPP waveguide ROG is that the frequency lock-in used to suppress the influence of reciprocal noises on velocity detection can be achieved by thermo-optical modulation of the LRSPP waveguide resonator, which is controlled by the feedback loop shown as Fig. 1. Fig. 5 shows the frequency shift as a function of the heating power with different radius. A small change of heating power can bring in a big frequency shift. The order of magnitude of the frequency-turning rate is about several hundred of megahertz per milliwatt.

Discussion

We have shown above that the active LRSPP waveguide ROG has properties of high sensitivity, low polarization error, and suppressing reciprocal noises by thermo-optical modulation of the LRSPP ring resonator. Here, we address the reasons for the performance improvement of the ROG. In this ROG, the LRSPP waveguide resonator with gain medium was pumped by a vertical pumping source with wavelength of 982 nm. This strategy has significant advantages to restrain the pump noise due to the following reasons. Firstly, as the pump light irradiates vertically into the LRSPP waveguide, the pump light would be hardly coupled into the LRSPP ring resonator. Additionally, even though a 982 nm LRSPP mode is excited in the LRSPP waveguide resonator, it will attenuate soon because the propagation loss of an LRSPP mode at 982 nm is much higher than that at the work wavelength of 1550 nm. The noise arising from the

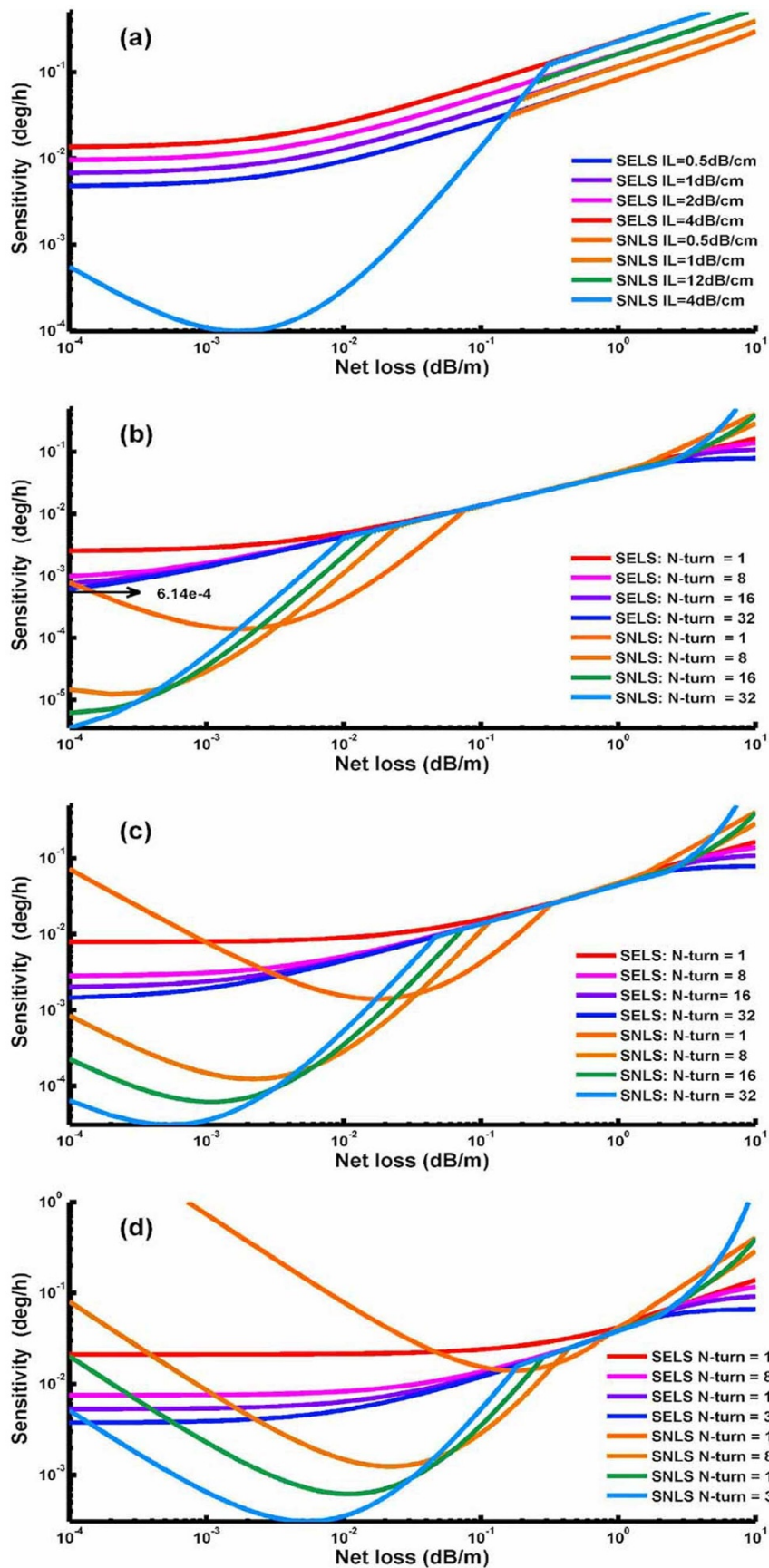


Figure 3 | (a) Relation of optimized SNLS, SELS and net loss with different intrinsic losses (IL) and relation between optimized SELS, SNLS and net loss with k_{min} of (b) 0.01%, (c) 0.1%, and (d) 1% with different N_{turn} . The dotted line (observed in large scale) represents SNLS and solid line represents SELS.

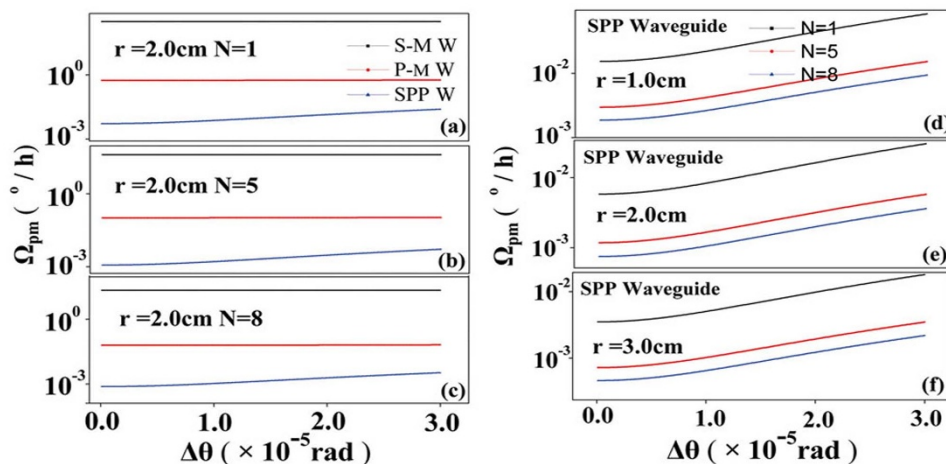


Figure 4 | The maximum zero drift of gyroscope constructed by (a) single mode waveguides, (b) polarization maintaining waveguides and (c) LRSP waveguides with different N_{turn} at $r = 2$ cm. (d)–(f) show the maximum zero drift of LRSP waveguide ROG with different N_{turn} and $r = 1$ cm, 2 cm and 3 cm.

interference of pump light source therefore can be avoided by using this pumping strategy.

In this loss compensation strategy, Fig. 2 and Fig. 3 show that the LRSP waveguide ROG's limited sensitivity is decided by the bigger one of SNLS and SELS. As shown in Fig. 2, SNLS and SELS vary with different trends with an increasing k . Therefore, there is an optimal value of k corresponding to the limited sensitivity when the net loss is a fixed value. From Fig. 2, we found that as the SNLS and SELS are essentially the uncertainties of sensitivity induced by two different mechanisms, and the limited sensitivity is finally determined by the bigger one. So the optimal parameter can be obtained by changing the coupling ratio until the bigger one of SNLS and SELS having the min value. The calculated optimal SNLS, SELS are shown in Fig. 3, which indicates that the limited sensitivity is mainly determined by SELS. It should be noted that the influence of SNLS on the limit sensitivity in active LRSP waveguide ROG is more obvious than that of conventional optical gyros with gain. For the conventional optical gyroscope with gain, the limited sensitivity is mainly determined by the SELS because SNLS is always a small value which can be neglectable²³. For active LRSP waveguide ROG, however, SNLS plays a more important role compared with the conventional optical gyroscope. As shown in Fig. 3, when the net loss is at a low level (e. g. below 10^{-1} dB/m) for $N_{turn} = 1$ in Fig. 3(d), the SNLS is bigger than SELS and it becomes the major limit to the sensitivity.

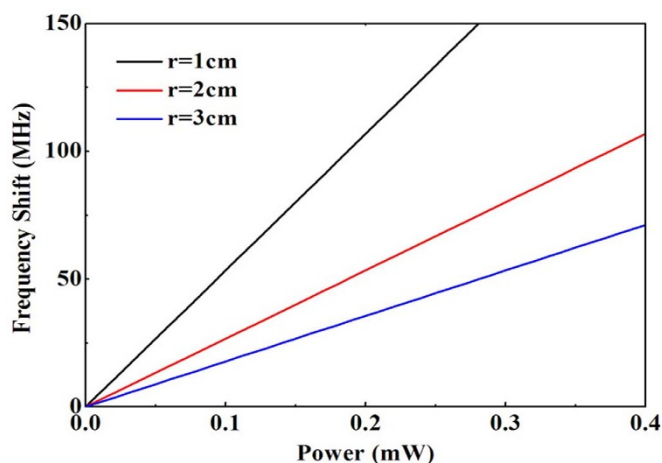


Figure 5 | Frequency shift at different heating power with different radius.

For multi-turn resonator, The length and the effective area of the ring resonator are written as²² $L = N_{turn} \times 2\pi r$ and $A = N_{turn} \times \pi r^2$, where, N_{turn} is the number of turns of the multi-turn resonator. As shown in Fig. 3, when the radius of the resonator is 2 cm, the calculated order of the limited sensitivities of LRSP waveguide ROG with single-turn and multi-turn resonator are 10^{-3} deg/h and 10^{-4} deg/h respectively, which have reached the accuracy level of precise gyroscope. The ROG with multi-turn ring resonators have a higher sensitivity than that with single-turn, mainly because that the effective area of resonator is increased by the number of turns. As shown in Fig. 3(b), (c) and (d), the optimized SELS decreases fast with an increasing N_{turn} , and has a best value of $\sim 10^{-4}$ deg/h. For a single-ring resonator with an ultra small value of net loss (e.g. smaller than 10^{-4} dB/m), the SNLS is the dominating factor of limited sensitivity. However, the SNLS for multi-turn situation decreases rapidly which improves the sensitivity greatly. In addition, it should be noted that when using this optimizing strategy as mentioned above, the min value of coupling ratio k_{min} has big influence on the results. The sensitivity increases as the k_{min} decreases. It also shows that the bigger the k_{min} is, the more improvements the multi-turn ring resonator brings in.

Another improvement from multi-turn resonator is in the pumping system. When the intrinsic loss of the ring resonator decreases significantly, the power of pump light should be accurately controlled to avoid lasing of the resonator, which is a big challenge for the control-system of pump light. However, the multi-turn ring resonator brings in more intrinsic loss than that of the single-turn one and requires bigger pumping power to compensate the system loss. This benefits the practical realization of loss compensation. In all, the multi-turn ring resonator lowers the required accuracy of the pumping-control-system and enhances the feasibility of the gyroscope's practical application.

In addition to the shot noise and spontaneous emission noise, polarization fluctuation is also a serious noise to ROG²⁴. However, LRSP waveguide only supports TM polarization mode, and has polarization extinction ratio of more than 40 dB which is superior than that of the conventional single-mode waveguide and the polarization maintaining waveguide¹⁴. The maximum zero drift caused by polarization mismatch of the input light can be expressed as $\Omega_{pm} \approx B[\sin^2 \Delta\theta + \sin 2\theta \sin 2(\theta - \Delta\theta) \sin^2(\Delta\lambda/2)]$, where $B = c\lambda_a / 4\pi AF$ and the polarization extinction ratio is expressed as $10\lg(1/\sin^2\theta)$. As a result, the Ω_{pm} of LRSP waveguide ROG can be reduced by the high polarization extinction ratio of LRSP waveguide, and be further reduced by increasing the effective area of ring resonator. As



shown in Fig. 4 (a)–(c), the Ω_{pm} of LRSP waveguide ROG is 1.47×10^{-3} deg/h when $N_{turn} = 8$, which is about 10^2 times smaller than that of maintaining waveguide resonator, and about 10^4 times smaller than that of single mode waveguide resonator. As shown in Fig. 4 (d)–(f), for $N_{turn} = 8$, the value of Ω_{pm} of LRSP waveguide ROG with $r = 3$ cm is 8.90×10^{-4} deg/h, which is 39.7% and 76.5% of that with $r = 2$ cm and $r = 1$ cm, respectively. The results indicate that the maximum zero drift of resonant optical gyroscope using LRSP waveguide is much lower than that of using single mode waveguide and maintaining waveguide, and is closely related to the resonator radius and number of turns.

In our proposed ROG, PZT²⁵ or tunable laser⁵ is no longer a necessity. Electro-optical multiplexing is a peculiar property of LRSP waveguide distinct from conventional optical waveguides. It is because the LRSP waveguide can support both optical signal and electrical signal simultaneously through the core layer of LRSP waveguide constructed by metal strip. Thermo-optical modulation is an effective method to tune the mode effective refractive index of optical waveguides by thermo-optical effect introduced in Ref. 26,27. As the LRSP waveguide has the electro-optical multiplexing property, the metal core layer of LRSP waveguide can serve as both optical transmission media and heating electrode. The temperature of the metal layer and surrounded cladding layers can be changed by adding appropriate electric signal directly through in the metal core layer, leading to a change of the mode effective refractive index of the LRSP waveguide.

The fluctuations in the resonant frequency and/or the central frequency of the laser caused by reciprocal noises can be compensated by using the metal layer of the LRSP waveguide simultaneously as waveguide and heating element. The compensated frequency Δf by heating power P_A can be expressed as $\Delta f = [(1/N_{eff})(dN_{eff}/dT) + \alpha_{sub}]\Delta T(P_A)c/\lambda_a$, where $\Delta T(P_A) = P_A t_W / [S_H k_W (1 + 0.88 t_W / W)]$, $W = 2W_H$, S_H is the area of the heater, W_H is the width of the heater, t_W is the waveguide thickness, k_W is the thermal conductivity of the cladding, α_{sub} is the thermal expansion coefficient of the substrate, dN_{eff}/dT is the thermo-optic coefficient of the LRSP waveguide^{26,27}. The frequency modulation coefficient in this proposed ROG based on thermo-optical modulation to the LRSP ring resonator shown in Fig. 5 is approximate to the frequency modulation of laser in ROG system²⁸. As a result, a same order of magnitude of frequency lock-in precision can be achieved on conditions of with same servo circuits and devices. The reciprocal noises can be effectively suppressed by using the frequency lock-in system based on thermo-optical modulation to the LRSP ring resonator.

To conclude, this study presents a novel integrated ROG based on an active LRSP waveguide resonator. According to the properties of LRSP waveguide, we deduced the mathematic model of the shot noise limited sensitivity (SNLS) and the spontaneous emission limited sensitivity (SELS) of the presented ROG. Our researches reveal that the limited sensitivity of this LRSP waveguide gyroscope is finally decided by the bigger one of SNLS and SELS. We further constructed LRSP waveguide ROG with multi-turn resonator which shows a high sensitivity of $\sim 10^{-4}$ deg/h. The achieved sensitivity reaches the accuracy of delicate gyroscopes such as laser gyroscopes which have been widely used in inertial navigation system with high performance. Meanwhile, we have also shown in this paper that the influences of propagation loss, polarization fluctuation and reciprocal noises on conventional optical waveguide ROG are well solved by using LRSP waveguide. LRSP waveguide resonator pumped under a vertical pumping source compensates the propagation loss of LRSP waveguide and has low pump noises. The high polarization extinction ratio of LRSP waveguide significantly reduces the ROG's polarization error. The self-turning of LRSP waveguide resonator based on electro-optical multiplexing can effectively suppress the reciprocal noises. Therefore, LRSP waveguide

can greatly improve the ROG's performance and appears to be an ideal medium for constructing compact integrated optical gyroscope with high performance for inertial navigation systems.

Methods

Principle of LRSP waveguide ROG. Lightwave from a laser is equally divided by the coupler C1 into two beams. The two beams are modulated by phase modulators PM1 and PM2 with the modulation frequencies of f_1 and f_2 , respectively. The modulated signals launch into the LRSP waveguide resonator through coupler C4. The clockwise (CW) and counterclockwise (CCW) beams from the LRSP waveguide resonator are detected by photodetector PD1 and PD2, respectively. The output electrical signal of PD2 is demodulated by the lock-in amplifier LIA2. The output signal of LIA2 shows a difference between the central frequency of the laser and the resonant frequency of the CCW light-wave in the ring resonator. This difference is the feedback signal to the resonator to turn the resonant frequency of the CCW light-wave to the central frequency of the laser based on thermo-optical modulation. As a result, the fluctuations in the resonant frequency and/or the central frequency of the laser induced by the environmental variation are compensated. The demodulated signal of the CW light-wave from LIA1 is the open-loop's readout which is proportional to the rotation rate.

The phase modulation spectroscopy technique is an effective way for detecting the weak rotation signal by using the two phase modulators PM1 and PM2 to modulate the phase of the two input light waves divided from C1 shown in Fig. 1. f_1 and f_2 is the frequency of modulation signal added on PM1 and PM2, respectively. The selection of values of f_1 and f_2 determines the demodulated signal slope at resonant frequency which has been discussed in Ref. 29 in details. The proportional integrator (PI) is adopted to eliminate the residual error at the lock-in frequency.

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Author contributions

T.Z. inspired the idea and guided and supervised the work. G.Q., X.-J.X., Y.-Y.W. and F.S. performed the calculations and wrote the manuscript. J.-Y.W. prepared the figures. R.-Z.L. and X.-Y.Z. provided advices and helpful theoretical discussion. All authors reviewed the manuscript and discussed the results.

Additional information

Supplementary information accompanies this paper at <http://www.nature.com/scientificreports>

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