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Spontaneous emission noise in long-range surface plasmon polariton waveguide based optical gyroscope

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Spontaneous emission noise is an important limit to the performance of active plasmonic devices. Here, we investigate the spontaneous emission noise in the long-range surface plasmon-polariton waveguide based optical gyroscope. A theoretical model of the sensitivity is established to study the incoherent multi-beam interference of spontaneous emission in the gyroscope. Numerical results show that spontaneous emission produces a drift in the transmittance spectra and lowers the signal-to-noise-ratio of the gyroscope. It also strengthens the shot noise to be the main limit to the sensitivity of the gyroscope for high propagation loss. To reduce the negative effects of the spontaneous emission noise on the gyroscope, an external feedback loop is suggested to estimate the drift in the transmittance spectra and therefor enhance the sensitivity. Our work lays a foundation for the improvement of long-range surface plasmon-polariton gyroscope and paves the way to its practical application.

Surface plasmon polaritons (SPP) based devices could be highly integrated with the unique ability of breaking the optical diffraction limit. However, SPP suffers high propagation loss in the metal-dielectric interface remaining many promising applications impractical. To reduce SPP's loss, active plasmonic devices with gain is proposed. Since Stockman raised the theory of stimulated emission based gain of SPP¹, it turns out to be possible to compensate the propagation loss by an external gain²⁻⁴. Various gain materials have been used in experiment, such as dye molecules⁵⁻⁷, Er³⁺^{8,9} and semiconductor quantum dots^{10,11}. The performance of plasmonic devices is improved but still limited by the spontaneous emission noise. Recently the long-range surface plasmon polaritons (LRSP) waveguides is applied in active plasmonic devices and net gain is achieved with small spontaneous emission noise thus becoming low-noise plasmonic devices^{5,12}.

Optical gyroscopes are high-performance rotation sensors for inertial navigation system based on Sagnac effect. Their performances are improved by introducing the LRSP waveguides. We have presented the theory of optical resonant gyroscope based on LRSP waveguide with gain and demonstrated its unique advantages resulting from SPP's various features, such as single-polarization, electro-optical multiplex, and gain enhancement¹³. The sensitivity of LRSP gyroscope are mainly limited by two sources of noises, e.g. shot noise limited sensitivity (SNLS) and spontaneous emission limited sensitivity (SELS). In addition to Ref.13, the spontaneous emission not only produces an uncertainty on the detection of the light frequency in the gyroscope which results in SELS, but also import a noise with a certain power into the gyroscope system. In another words, not only the limited sensitivity, but also some other performances such as transmittance spectra, signal-to-noise-ratio, would be effected by the spontaneous emission noise.

In this paper, we are to figure out how the energy of spontaneous emission behaves and makes differences in LRSP based optical gyroscope. We study the incoherent multi-beam interference of spontaneous emission in the gyroscope and establish a theoretical model to make a rough estimate of its impact on the gyroscope's transmittance spectra, SNLS and SELS. Problems for practical application are discussed and an external feedback loop is suggested to reduce the negative effects of the spontaneous emission noise.

Results

The spontaneous emission plays an important role in light amplification based gain¹⁴, especially in Stimulated emission in SPP⁸. In a plasmonic amplifier, the spontaneous emission exhibits a complex behavior due to a variety of energy decay channels engendered by the metal¹². We proposed an active gyroscope based on LRSP resonator

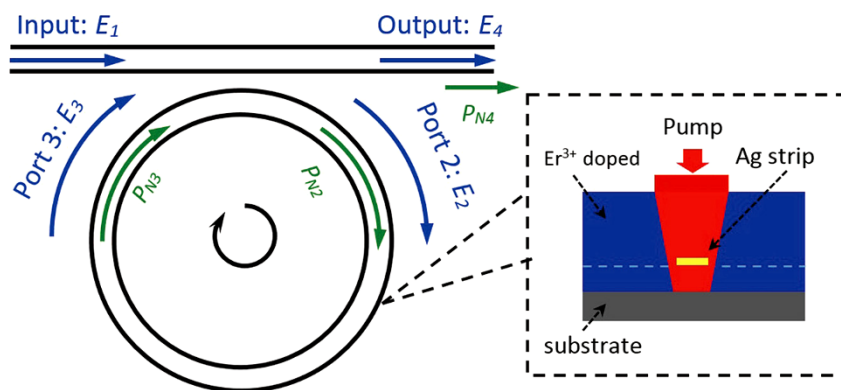


Figure 1 | Schematic diagram of the LRSP waveguide ring resonator. Insert shows the cross-section of the LRSP waveguide.

with gain, as shown in Fig. 1¹³. In our model, apart from non-radiation channels, the spontaneous emission's energy into short-range surface plasmon polariton would decay fast with the increase of propagation length. For the energy into LRSP, we used a vertical pumping mechanism to realize the optical gain and the gain is anisotropic depending on the structure and gain material (for example, dye molecule¹²). As a result the coupling of spontaneous emission with the signal LRSP is weak. So the major part of the SE's energy propagating in the LRSP resonator is in the radiation channel which is a bit far away from the metal (~ 100 nm¹²).

We assume that the loss of the LRSP resonator is nearly compensated by gain with carefully control on the pumping power. The intensity of the propagating wave in the LRSP waveguide with gain follows the function that: $dI/dz = AP_p + gI$ (where I is the propagating wave's intensity, A is a constant, P_p is the pumping power and g is the gain)¹⁵. In our model, g is negative and the spontaneous emission noise would attenuates propagating along the waveguide.

One of the most significant differences between spontaneous emission and stimulated emission is that, the phases of spontaneous emitted photons are random, but the stimulated emitted photons' are the same as the stimulating photons, i.e. the spontaneous emitted light is incoherent but the stimulated emitted is coherent¹⁶. As the light in the ring resonator is essentially under multiple beam interference, in the LRSP gyroscope the spontaneous emitted light and stimulated emitted light are substantially oscillating in two different forms, i.e. coherent interference and incoherent interference and superposing with each other.

The LRSP resonator is shown in Fig. 1. E_1, E_2, E_3, E_4 are the amplitudes of signal LRSP's electric field in the four ports of the directional coupler and P_{N2}, P_{N3}, P_{N4} are the powers of the spontaneous emission noise at port 2–4. Here, we consider only the clockwise case. We assume that the resonator is single-mode and the input signal is single-frequency.

For the coherent interference of the signal LRSP, the relationships of E_1, E_2, E_3, E_4 are given by¹⁷

$$E_2 = \sqrt{1-\delta}(-jE_1\sqrt{k} + E_3\sqrt{1-k}) \quad (1)$$

$$E_3 = \sqrt{1-\delta}E_2 \exp\left(-\frac{\rho_{net}}{2}L - j\beta L\right) \quad (2)$$

$$E_4 = \sqrt{1-\delta}(E_1\sqrt{1-k} - jE_3\sqrt{k}), \quad (3)$$

where δ is the insert loss of the coupler, k is the coupling ratio of optical power coupled from the top straight waveguide into the ring, L is the ring's perimeter, ρ_{net} is coefficient of net loss which represents the propagation loss of the LRSP waveguide with gain, and β is the propagation constant. Combining Eq. (1) – (3) yields the power transmittance¹⁷

$$T(\phi) = \frac{E_4^2}{E_1^2} = (1-\delta) \times \frac{(x-y)^2 + 4xy \sin^2(\phi/2)}{(1-xy)^2 + 4xy \sin^2(\phi/2)} \quad (4)$$

with $x = \exp(-\rho_{net}L/2)$, $y = \sqrt{1-k}$, $\phi = \beta L = 2\pi N_{eff}L/\lambda$, where λ is the free-space optical wavelength of the input signal light, N_{eff} is the effective index of the guided LRSP mode.

However, the incoherent interference of spontaneous emission noise could be very different. An output spontaneous emission noise is produced even with zero input signal when the LRSP waveguide is under pump¹². This zero-in output spontaneous emission also exists in the LRSP resonator and after an incoherent multi-beam interference outputs from port 4 resulting in a zero-in noise for the gyroscope system. Assuming the power of the initial spontaneous emission noise is η . It should be noted that η is not a constant value in a real gyroscope system. In the following calculation, we would set it varied that changes in a certain range. After the initial spontaneous emission first output at port 3, it's divided by the coupler into $\eta(1-\delta)(1-k)$ at port 2 and $\eta k(1-\delta)$ at port 4 (noted that we assume the coupling ratio of spontaneous emission is approximately the same as the signal LRSP as their center wavelength is the same. In addition, the full width of half maximum (FWHM) of spontaneous emission is dozens of nanometers⁵ and the coupling between plasmonic waveguides trend to be broadband^{18,19}). The process of the power changes of spontaneous emission noise are shown in Table 1.

Plus the n powers in Table 1 together, and the ultimate outputs in the three ports are given as follows,

$$P_{N3} = \eta \frac{1}{1 - (1-\delta)(1-k) \exp(-\rho_{net}L)} \quad (5)$$

Table 1 | The process of the power change of spontaneous emission noise in the resonator

	P_{N3}	P_{N2}	P_{N4}
$n=1$	η	$\eta(1-\delta)(1-k)$	$\eta k(1-\delta)$
$n=2$	$\eta(1-\delta)(1-k) \times \exp(-\rho_{net}L)$	$\eta(1-\delta)^2(1-k)^2 \times \exp(-\rho_{net}L)$	$\eta k(1-\delta)(1-\delta)(1-k) \times \exp(-\rho_{net}L)$
...
n	$\eta(1-\delta)^{n-1}(1-k)^{n-1} \times \exp[-(n-1)\rho_{net}L]$	$\eta(1-\delta)^n(1-k)^n \times \exp[-(n-1)\rho_{net}L]$	$\eta k(1-\delta)(1-\delta)^{n-1}(1-k)^{n-1} \times \exp[-(n-1)\rho_{net}L]$

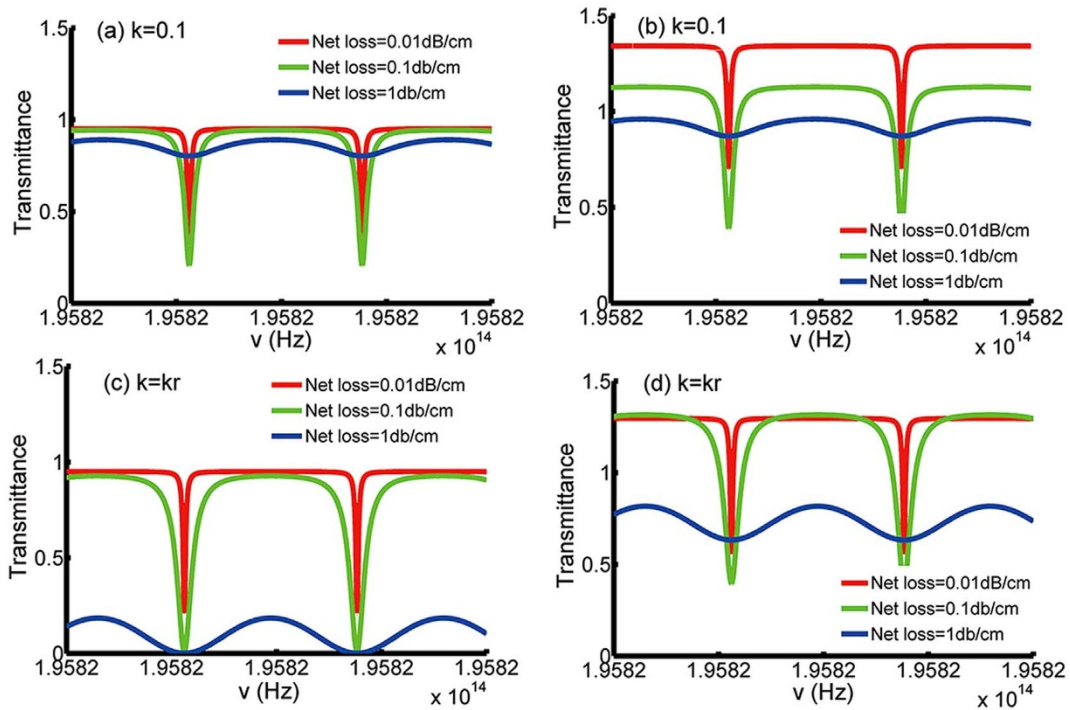


Figure 2 | Transmittance spectra without, (a) (c) and with, (b) (d) the power of spontaneous emission for different net losses. (a) (b) are for fixed coupling ratio of 0.1 and (c) (d) are for optimum coupling depth.

$$P_{N2} = \eta \frac{(1-\delta)(1-k)}{1-(1-\delta)(1-k)\exp(-\rho_{net}L)} \quad (6)$$

$$P_{N4} = \eta \frac{(1-\delta)k}{1-(1-\delta)(1-k)\exp(-\rho_{net}L)} \quad (7)$$

Next, we would show how these noise powers impact the gyroscope's performances, including transmittance, SNLS and SELS.

Transmittance. For a real gyroscope system, the photoelectric effect based photo-detector is non-selective to light with different wavelengths to some extent²⁰ which means power of noises with various wavelengths could be detected and affect the output results. Therefore, the spontaneous emission with a relatively wide spectrum could make an unnegligible difference on the gyroscope's performance (the optical resonant gyroscope requires highly narrowed input light, typically the input laser's linewidth has to be less than 10 MHz²¹⁻²³). Based on the discussion before, the power transmittance at port 4 is driven as,

$$T' = \frac{T \times P_{in} + P_{N4}}{P_{in}} = T + \frac{P_{N4}}{P_{in}} = T + \frac{\eta}{P_{in}} \times M, \quad (8)$$

where $M = \frac{(1-\delta)k}{1-(1-\delta)(1-k)\exp(-\rho_{net}L)}$ and P_{in} is the power of the input signal LRSP at port 1. It can be seen from Eq. (8) that the spontaneous emission noise introduces a frequency-independent upward drift to the transmittance curve. For a given gyroscope system, this transmittance drift is related to the ratio of spontaneous emission's noise, η and input signal. Fig. 2 shows the transmittance spectra without, (a) (c) and with, (b) (d) the power of spontaneous emission for different net losses. It's obvious that the power of spontaneous emission expose a big drift in the transmittance curve which would certainly make a difference on the sensitivity. For practical application, an external circuit should be designed to eliminate the drift. We propose a feedback loop. Its basic working principle is to store the drift under zero input signal

and when with none-zero input, feed it back to the output. Thereby, the gyroscope produces a stable output and an improved sensitivity.

SNLS. The sensitivity of resonator gyroscope limited by signal-to-noise-ratio (SNR) is expressed as²⁴

$$\Delta\Omega \cong \frac{\lambda L}{4A} \frac{\sqrt{2}\Delta f_{FWHM}}{SNR}, \quad (9)$$

where A is the area enclosed by the ring, Δf_{FWHM} is the FWHM of the resonant peak. The signal current from the photodetector is given by²⁴

$$i_s = \frac{\eta_D e}{h\nu} (T_{max} - T_{min}) P_{in}, \quad (10)$$

where η_D is the quantum efficiency of the photodetector, e is the electronic charge, h is Planck's constant, ν is the frequency of input signal, and T_{max} and T_{min} are the maximum and minimum values of the transmittance in Eq. (8), respectively. If the limiting noise is shot noise, the rms noise current from the photodetector is given by²⁴

$$i_n = e \sqrt{\frac{\eta_D P_{in}}{\tau_D h\nu} \times \left[T_{max} + \frac{\eta}{P_{in}} \times M \right]} \quad (11)$$

combining Eq. (9) - (11) with $SNR = i_s/i_n$, the Shot Noise limited sensitivity is given as

$$\Delta\Omega_{SNLS} \cong \frac{\lambda L}{4A} \times \frac{\sqrt{2}\Delta f_{FWHM}}{\sqrt{\frac{\eta_D P_{in}}{h\nu} \times \frac{T_{max} - T_{min}}{T_{max} + \frac{\eta}{P_{in}} \times M}}} \quad (12)$$

In comparison with the SNLS in Ref. 13, the SNLS affected by spontaneous emission noise increases by the factor of $\sqrt{1 + \eta M / (P_{in} T_{max})}$. It can be understood that after introducing the power of the spontaneous emission noise, the SNR of the ring resonator is reduced, thereby worsening the SNLS.

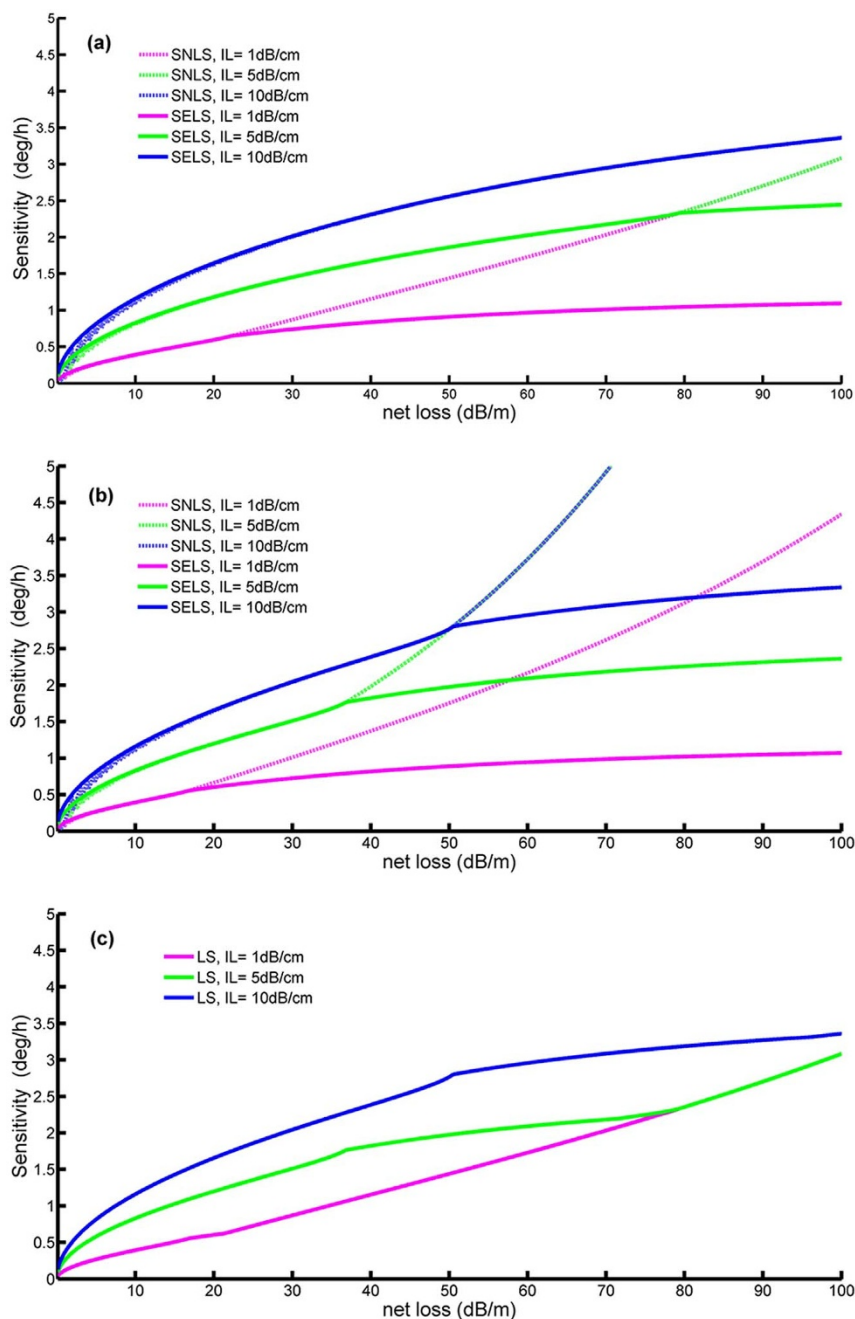


Figure 3 | Relation between Sensitivity and net loss with different intrinsic losses. (a) is for situation without the power of spontaneous emission and (b) with. (c) shows the gyroscope’s ultimate sensitivity with a feed-back loop.

SELS. The power of spontaneous emission mainly impacts the mean photon number of the resonant ring which is given by²⁵

$$\langle n \rangle = \frac{N_{eff} P_c L}{2h\nu c}, \tag{13}$$

where P_c is the power of light in the ring. The power of light in the ring includes signal LRSPP, P_{in} , and the spontaneous emission noise at port 2, P_{N2} , as follows

$$P_c \approx \frac{1}{\pi} FP_{in} + P_{N2} \tag{14}$$

combining Eq. (6) and Eq. (14), following the derivation in the supporting information of Ref.13, we get the SELS as

$$\Delta\Omega_{SELS} \cong \frac{\lambda c}{4\sqrt{2\pi}AN_{eff}} \times \left[\frac{\alpha_{intr} L h \nu}{\tau_D (FP_{in} + \frac{1-k}{k} \pi M \eta)} \right]^{1/2}, \tag{15}$$

where α_{intr} is the propagation loss of LRSPP the waveguide without gain (intrinsic loss, IL), F is the finesse of the gyroscope. In comparison with the SELS in Ref. 13, the SELS reduces by the factor of $\sqrt{1/[1+(1-k)\pi M \eta/(kFP_{in})]}$. It can be understood that after introducing the power of the spontaneous emission noise, the total number of photons in the ring resonator increases and thus the disturbance of a single spontaneous emitted photon on the phase of the signal LRSPP is weakened relatively.

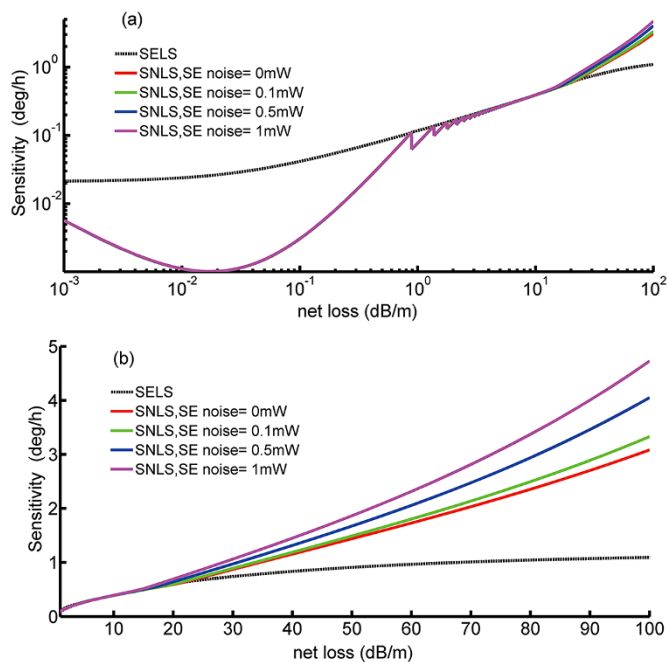


Figure 4 | Relation between Sensitivity and net loss for different powers of spontaneous emission. (a) is for a net loss from 10^{-5} dB/cm to 1 dB/cm, and (b) is from 0.01 dB/cm to 1 dB/cm.

Fig. 3 shows the relations between net losses and the SNLS, SELS with different intrinsic losses. Fig. 4 shows the relation between SNLS, SELS and net loss with different spontaneous emission powers. It's obvious that the impact of the spontaneous emission's power on the sensitivity can not be ignored.

Discussion

The model is numerically calculated to show the impact of spontaneous emission on the gyroscope (see methods in detail). For a given gyroscope, the drift in the transmittance spectra concerns with M , i.e. the coupling ratio and net loss of the LRSPP waveguide. The transmittance spectra under fixed coupling ratio and optimum coupling depth (with $k = k_r = 1 - (1 - \delta) \exp(-\rho_{net}L)^{26}$) are compared with each other. In Fig. 2, (a)(b) are for fixed coupling ratio of 0.1 and (c)(d) are for optimum coupling depth. Here, the power of input signal LRSPP is 1 mW and the power of spontaneous emission is set to be 0.7 mW. Comparing Fig. 2 (a) and Fig. 2 (b), with fixed coupling ratio, the drift decreases with the net loss increases. This could be easily understood that with increased loss, the power of spontaneous emission would decay faster, thereby resulting in lower output noise and lower upward drift in transmittance curve. On the other hand, comparing Fig. 2 (c) and Fig. 2 (d), the drift increases with the net loss which results from different net losses and k_r . Calculated k_r for net losses of 0.01 dB/cm, 0.1 dB/cm and 1 dB/cm are 0.0527, 0.0771 and 0.2888 respectively. The two opposite trends indicate that the effects of coupling ratio on the upward drift is bigger than that of net loss. The upward drift in the transmittance spectra adversely affects the angular velocity detection of the gyroscope.

Fig. 3 shows the sensitivity is (a), (b) worsen by the drift in transmittance and (c) improved by the feedback loop mentioned before. Here, the same optimizing strategy of coupling ratio k as that in Ref. 13 is used and η is 0.7 mW. In comparison with Fig. 3(a) and Fig. 3(b), it can be found can be clearly seen that the impact of spontaneous emission on SELS is small and the SNLS is significantly strengthened by it. When the net loss is big, for example 0.2 dB/cm for an IL of 1 dB/cm, SNLS becomes bigger than SELS. As a result, the cross point of SNLS and SELS goes down to lower net loss. It's obvious that the sensitivity of the gyro could be improved by the

feed-back loop as mentioned before. When the loss is higher than the cross point of SNLS and SELS, the feed-back loop could enhance the SNR and therefore suppress the SNLS. Fig. 3(c) shows the ultimate limited sensitivity (LS) in a real gyroscope system with a feed-back loop. The improvement from the feed-back loop relates to the net loss and IL. For example when the net loss is 1 dB/cm and IL is 10 dB/cm the LS is reduced from 10 deg/h to 3 deg/h and when the net loss is 0.5 dB/cm and IL is 5 dB/cm the LS is reduced from 2.76 deg/h to 1.98 deg/h.

Fig. 4 shows the impact of the power of spontaneous emission on the sensitivity. Fig. 4 (a) is for net loss ranging from 10^{-5} dB/cm to 1 dB/cm and Fig. 4 (b) from 0.01 dB/cm to 1 dB/cm. Here, the intrinsic loss is 1 dB/cm and the serrated section in Fig. 4 (a) results from a minimum step value of k^{13} . It can be clearly seen in Fig. 4 (a) that with increased power of spontaneous emission, the SELS changes very little (all curves for different powers of spontaneous emission overlap in the black dashed line). SELS is still greater than SNLS with low net loss, e.g. smaller than 0.01 dB/cm. It could be understood that loss net loss corresponds to low optimized coupling ratio making the spontaneous emission noise mainly decay in the ring resonator. On the other hand, Fig. 4 (b) shows that SNLS increases faster with bigger powers of spontaneous emission. It's easy to understand that bigger spontaneous noise leads to lower SNR and worse SNLS. Above all, the power of spontaneous emission worsens the SNLS and a feed-back loop is required to reduce this negative effects.

In conclusion, we investigated the performances of the LRSPP gyroscope taking into account the noise power of spontaneous emission. Our theoretical study shows that the propagating energy of spontaneous emission noise are mainly in the radiation channel and undergoes an incoherent multi-beam interface in the resonator, forming a steady noise power in the output. This output noise produces a drift in the transmittance spectra and lowers the SNR of gyroscope which results in increased SNLS. However it makes small modification on SELS. For high net loss, e.g. above 0.2 dB/cm for an IL of 1 dB/cm, the spontaneous emission strengthens the SNLS to be the main limit to the gyroscope's sensitivity. In a practical gyroscope system, an external feedback loop is suggested to estimate the drift in the transmittance spectra and reduce the negative effects of the spontaneous emission on the sensitivity of the gyroscope. The ultimate limited sensitivity is improved by the feed-back loop, e.g. from 10 deg/h to 3 deg/h with a net loss of 1 dB/cm and IL of 10 dB/cm. Although the experiment of LRSPP waveguide give us some support in determining the power of spontaneous emission¹², experimental work of LRSPP gyroscope is needed and ongoing to demonstrate the practical performance of LRSPP gyroscope.

Methods

The LRSPP waveguide resonator with gain medium is pumped under a vertical pumping light with wavelength of 982 nm, and the signal LRSPP's wavelength is 1550 nm. The LRSPP waveguide consists of Si substrate, 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 ⁸.

The radius r of the ring resonator is 2 cm, the width and thickness of silver film are 6 mm and 11 nm respectively, the power of input signal is 1 mW, the insert loss of the directional coupler is 5%, and the quantum efficiency and integration time of the photo detector are 0.9 and 1 h, respectively. The propagation loss of LRSPP the waveguide without gain is in the order of magnitude of 1 dB/cm^{14,27}. For a 2.7 mm long waveguide with an input power of 2.1 mW and net gain of 10%, the output SE noise could be more than 1 mW¹². Although our LRSPP resonator is of negative gain, the scale of our pumping area is far bigger which could result in bigger SE noise. In this letter, the range of magnitude of η is set to 0 mW ~ 1.5 mW. The original driving process of SNLS and SELS could be seen in Ref. 13 in detail.

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Author contributions

Y.-Y.W. performed the calculations and wrote the manuscript. T.Z. provided advices and helpful theoretical discussion. All authors reviewed the manuscript and discussed the results.

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