Optical Gyroscope Based on Multi-gap Surface Plasmon Optical Waveguide

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Abstract

In this paper, a kind of optical gyroscope based on multi-gap surface plasmon optical waveguide was designed. The key component was multi-gap surface plasmon waveguide ring resonator. Through the finite element method, the dependence between the transmission characteristics of resonator and the number of metallic film, the gap width and the bending radius was calculated in details. The results show that the higher detection sensitivity can be obtained by optimizing the parameters of geometric structure. When the coupling ratio was over 60\%, the optimal metal film number was five, the optimal gap width was 1 \(\mu\text{m}\) and the optimal bending radius was 3 cm, the detection sensitivity of the optical gyroscope was up to 3 deg/h. The research can provide a theoretical basis for the miniaturization of integrated optical gyroscope.

Key Words: Integrated Optical Gyroscope, Optical Waveguide, Vertical Surface Plasmon, Multi-gap Structure, Sensitivity

1. Introduction

In recent years, optical gyro is becoming a major component of high performance angular rate sensor which has wide application prospect in the field of aerospace [1–3]. In order to meet the needs of application, it is urgent to make the optical gyroscope miniaturized, integrated and low power consumption. Because of its high reliability, small size and full solid state and other advantages, the micro optical gyroscope based on waveguide ring resonator has become one of the attractive candidates to achieve this goal [4–6].

Surface plasmon waveguide can realize the sub-wavelength transmission of optical signal, and it can meet the requirements of both the optical devices’ miniaturization and the integrated optical chips’ densification [7–10]. It has become a research topic about applying the structure of surface plasmon optical waveguide to the micro optical gyroscope based on waveguide ring resonator [11–13]. In 2011, L. O. Diniz et al. investigated and proposed a ring plasmon-polariton resonator as a promising platform for (bio) sensor devices, the research shows that the proposed structure not only has the advantages of low loss, and consequently a long propagation distance, but also a good lateral field confinement [12]. In 2013, Wei Li et al. proposed a thermo-optical controlled integrated plasmonics gyroscope based on long-range surface plasmon-polariton (SPP) waveguides. It has been shown that such plasmonic waveguide gyroscope can be used to conduct electric and optical signals simultaneously. The tunability of the sensitivity of the gyroscope was also discussed [13]. In 2013, Caterina Ciminelli et al. reported an InP ring resonator with an experimentally demonstrated quality factor (Q) of the order of 106 [6]. In 2014, Zhang T. et al. proposed a resonant type integrated optical gyroscope based on surface plasmon waveguide, the influence of waveguide size on the propagation loss was simulated. When the horizontal waveguide was formed in the ring cavity, the relationship between the sensitivity and the coupling ratio was
analyzed [14]. In 2014, F. Dell’Olio et al. reviewed the recent technological advances on the compact optoelectronic gyroscopes with low weight and high energy saving [4]. In 2017, Liang W. et al. reported on the implementation of an integrated passive gyroscope using a monolithic cavity [15]. In 2015, Hassan, S et al. described the fabrication of a novel plasmonic Bragg grating, consisting of a gold stripe [16]. In 2018, Ren, PS et al. reported the fabrication of long-range surface plasmon polariton biosensors consisting of thin narrow Au stripes embedded in a low refractive index [17]. According to the previous research, it is feasible to design optical gyroscope based on ring resonator adopting the surface plasmon optical waveguide and optical gyroscope can be fabricated with the state-of-the-art technology and tolerances.

However, the detection sensitivity of optical gyroscope is unsatisfactory because of medium’s higher propagation loss. In order to improve the sensitivity of integrated optical waveguide gyroscope, a new type of vertical surface plasmon optical waveguide gyroscope based on multi-gap is presented in the paper. Using this structure not only can reduce the contact area between optical signal and metallic surface, but also can balance the propagation loss and bend loss effectively, and improve the detection sensitivity.

In the second part of the paper, the basic structure of the key device of the vertical multi-gap surface plasmon optical gyroscope is introduced, and the method of calculating the waveguide loss is presented. In the third part, the calculation results are presented. The influence of the number of metallic film, the gap size of metal film and the bending radius on the loss are discussed, the relationship between the sensitivity and the coupling ratio is calculated based on the three kinds of combination method for optical gyro. The fourth part is the conclusion that the vertical multi-gap surface plasmon optical waveguide can effectively reduce the loss value and improve the sensitivity of optical gyroscopes.

2. Structure and Calculation Method

Multi-gap surface plasmon waveguide ring resonator is the key part of the optical gyroscope designed in this research as shown in Figure 1(a). And $R$ is the radius of the ring resonator in the figure; $k$ is the coupling coefficient of the resonant cavity port optical signal. The waveguide of the ring resonator is multi-gap surface plasmon waveguide, and its cross section is shown in Figure 1(b). The waveguide is composed of several vertical metallic silver thin films laid in the epoxy resin ZPU450 that have the same height and width, and the gap need to be left between the thin films. The width of the thin film is $w$, the width of each gap is $d$, the total height of the film and the gap is $h$. When the wave length is 1550 nm, effective refractive index of metallic silver is $n_{Ag} = 0.15 + 11.5i$, the effective refractive index of epoxy resin material ZPU450 is $n_{ZPU} = 1.45$. The metal layer structure of the waveguide not only can propagate optical signals, but also can propagate electrical signals, and can realize...
photoelectric mixing on the same chip. The imaginary part of the dielectric constant represents the ability to absorb light; the metal layer of the surface plasmon waveguide can be direct modulation for efficient tuning of the device. Based on the Signac effect, when the ring resonator is perpendicular to its plane and rotates at a rotation speed of \( \Omega \) an optical path difference may exist between the two beams in the cavity propagating in the clockwise (CW) and counterclockwise (CCW) directions. This optical path difference will cause a resonance frequency difference proportional to the rotational angular velocity \( \Omega \) so that the magnitude of the rotational angular velocity \( \Omega \) of the carrier is obtained. The resonant frequency difference \( \Delta f \) between the CW and CCW beams propagating in the optical ring resonator according to the Signac effect is given by [18]:

\[
\Delta f = \frac{4A}{n_{\text{eff}}\lambda L}\Omega
\]  

where \( A \) is the area enclosed by the resonator, \( L \) is the optical perimeter, \( n_{\text{eff}} \) is the waveguide refractive index, \( \lambda \) is the wavelength of the light, and \( \Omega \) is the rotation rate.

In this paper, the transmission characteristics of a multi-gap surface plasmon optical waveguide are analyzed by using Multi physical field simulation analysis software (COMSOL Multiphysics) based on the finite element method. As the optical waveguide formed in the ring cavity is in a bending state, and the bending radius is \( R \), it is necessary to adopt the axis symmetric coordinate. The boundary conditions for the curved waveguide are set during the analysis. The mesh size is set to extremely fine, and the calculation time is about a few minutes under Intel Core i5-5200U CPU@2.2GHz. The electric field distribution and effective refractive index \( n_{\text{eff}} = n_r + in_i \) can be obtained by modal analysis here \( n_i \) stands for the bending loss and the transmission loss.

3. Results and Discussion

For the ring resonator based on multi-gap surface plasmon waveguide, which is shown in Figure 1, the loss of a ring waveguide is very important. According to the reference [13], the paper studies the horizontal structure, the loss value is larger than the vertical structure, and the vertical structure can utilize the characteristics of the surface plasmon effectively in order to obtain higher sensitivity. So this paper set the total height of the ring waveguide as \( h = 8 \mu m \) and the width as \( w = 20 \text{ nm} \). Under the condition that wavelength is 1550 nm, the loss of the circular waveguide is calculated and discussed from three aspects: the number of metallic film, the size of the gap width and the bending radius.

Based on that, a ring resonator of optical gyroscope can be formed by choosing the optimal number of metallic film, gap width, bending radius of the curved waveguide, and the straight waveguide. Besides, the relationship between sensitivity \( \delta \Omega \) and coupling coefficient \( k \) can be calculated and discussed.

3.1 The Effect of the Number of Metallic Films in Ring Waveguide on Losses

Figure 2 shows the electric field distribution of the fundamental mode excited by a multi-slit surface plasmon waveguide consisting of a single strip and two metallic silver films. Here, the bend radius \( R = 3 \text{ cm} \) and the gap width is 0.6 \text{ nm}. As can be found from Figure 2, due to the waveguide in a curved state, the inside and outside

![Figure 2](image-url)
electric field distribution of the waveguide was asymmetric. The effective refractive index \( n_{eff} = 1.451 + 7.36e^{-6}i \) corresponds to Figure 2(a), and the effective index of the Figure 2(b) is \( n_{eff} = 1.451 + 6.35e^{-6}i \). Since the imaginary part of the effective refractive index corresponds to the bending and propagation losses of the waveguide, obviously, the loss of the waveguide structure formed by two metallic silver thin films is lower than that of the waveguide structure formed by the single metallic silver thin film.

The phenomenon is caused by the fact that, compared with a single metallic silver film, the contact area between the field and the metal material is reduced due to the gap between the two metal silver films, and accordingly the interaction between the field and the metal material is reduced, thus the waveguide loss is reduced, which is expected to further improve the sensitivity of the optical gyroscope. This is why the multi-gap surface plasmon waveguide is adopted to form the ring resonator that is the key component in the optical gyro.

Figure 3 shows the trend of loss with the number of metallic film at different bending radius when the total gap width between metallic films is 0.5 \( \mu \)m and 0.6 \( \mu \)m. From Figure 3, it can be seen that when the bending radius is constant, with the increase of the number of metallic thin films, the waveguide losses generally show an upward trend. When the number of metallic films is constant, the waveguide losses are increasing with the increase of the bending radius \( R \). The above phenomena can be explained in terms of field distribution. Figure 4 shows what the electric field distribution is like, when the metallic film is two, three and five respectively, and the total gap width is 0.6 \( \mu \)m and the bending radius is 5 cm. From Figure 4, compared with the two metallic silver films, when the total height and the radius are fixed, if the number of strips increases, the gap between the two metallic silver films will decrease, and the contact area between the field and the metallic material will increase. And when the interaction increases, the waveguide loss increases also.

![Figure 3](image)

**Figure 3.** The waveguide losses varies with the number of strips under different \( R \). (a) The gap width between metallic films is 0.5 \( \mu \)m \((d = 0.5 \mu \text{m})\) with different strips of 2, 4, and 5; (b) The gap width between metallic films is 0.6 \( \mu \)m \((d = 0.6 \mu \text{m})\) with different strips of 2, 4, and 5.

![Figure 4](image)

**Figure 4.** Electric field distribution of waveguide structures with different numbers with parameters, \( d = 0.6 \mu \text{m}, R = 5 \text{ cm} \). (a) Two metallic films with gap; (b) Four metallic films with gaps with gap; (c) Five metallic films with gaps with gap with parameters.
3.2 The Effect of Gap Size between Metallic Films in Ring Waveguide on Loss

The loss of resonator with a multi-gap ring-shaped surface plasmon waveguide varies with the size of the gap between the metallic films. Figure 5 shows that the losses of a ring resonator structure with the size of gap. The different curves represent different bending radius, which changes from 3 cm to 7 cm, and under the condition of certain bending radius, the gap size increased from 0.5 μm to 1 μm, the losses value shows a decreasing trend. Figure 6 shows the electric field distribution with different gap widths when the five metallic films waveguide structure forms a ring resonator with a bending radius of 3 cm. As the gap width between the metallic films increases, the contact area between the light energy and the metal waveguide structure decreases, so that the loss value decreases with the gradual increase of the gap width.

3.3 The Effect of Bending Radius in Ring Waveguide on Loss

When the total width of the waveguide structure is constant, the effective refractive index of the waveguide structure with different number of films is calculated with different bending radius. Figure 7 shows when the total gap width is 0.8 μm ($d = 0.8 \mu m$); (b) The total gap width is 0.9 μm ($d = 0.9 \mu m$).

Figure 5. The losses decrease with the increase of gap width between metallic films under different $R$. (a) Two metallic films; (b) Five metallic films.

Figure 6. Electric field distribution with different gap width waveguides at 5 strips, and $R = 3$ cm, and (a) The total gap width is 0.5 μm ($d = 0.5 \mu m$); (b) The total gap width is 0.6 μm ($d = 0.6 \mu m$); (c) The total gap width is 0.7 μm ($d = 0.7 \mu m$).
total gap width is \( d = 0.8 \) and \( d = 0.9 \) μm, the loss value in the ring resonator composed of different number of metallic thin films changes with the bending radius. Different curves represent different numbers of metallic thin films; each curve has the smallest loss value at a bending radius of 3 cm. This is because the bending loss decreases as the bending radius increases, while the propagation loss increases with the gradually increase of bending radius. Therefore, the curve shows that when the bending radius \( R = 3 \) cm, regardless of the value of the structure which may be 2, 3, or 4, the total loss reached the lowest point. Figure 8 shows the distribution of the electric field when the total gap width is 0.9 μm and the ring resonator with different bending radius \( (R = 2 \text{ cm}, R = 3 \text{ cm}, \text{ and } R = 4 \text{ cm}) \) is formed by five metallic structures. The smaller the bending radius, the larger the energy of the radiation to the outside, i.e., the larger the bending loss. This is an important factor for the larger cavity loss with the smaller bend radius.

### 3.4 Sensitivity of Optical Gyroscope

Sensitivity is one of the important indexes to measure optical gyroscope, which is affected by the performance of ring resonator. Therefore, this paper focuses on the characteristics of loss of multi-gap ring waveguide with different number of metallic thin films, different gap widths and different bending radius, so as to obtain the optimal sensitivity of the optical gyroscope with surface plasmon ring waveguide resonator. The sensitivity \( \delta \Omega \) of optical gyroscope is calculated by the expression (2)–(4) [19]:

\[
\delta \Omega = \frac{\lambda L \sqrt{2} \delta f_{1/2}}{4A \text{ SNR}} = \frac{\lambda \sqrt{2} \delta f_{1/2}}{2R \text{ SNR}} \tag{2}
\]

where:

\[
\delta f_{1/2} = \frac{c}{2N_{eff} \pi L} \left( 2 \pi - 2 \arccos \left( \frac{2M \sqrt{1 - K}}{M^2 (K - 1) - 1} \right) \right) \tag{3}
\]

\[
\text{SNR} = \sqrt{\frac{\eta I f_{\text{SNR}} - T_{\text{min}}}{2hf}} \tag{4}
\]

\[
T = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{2M \sqrt{1 - K} \cos \beta L + (1 - K) + M^2}{1 + 2M \sqrt{1 - K} \cos \beta L + M^2 (1 - K)} \tag{5}
\]

\[
M = \exp(-\alpha L) \tag{6}
\]

In order to meet the application needs of miniaturization, and based on the above calculation results of multi-gap surface plasmon optical waveguide, and the three factors of the number of thin films, the width of the gap and the radius of bend in the waveguide structure three structures with smaller losses were chosen to calculate the sensitivity of their corresponding optical gyroscopes.

- (a) The structure of 3 metallic films and the total gap width is 0.7 μm;
- (b) The structure of 4 metallic films and the total gap width is 0.8 μm;
- (c) The structure of 5 metallic films and the total gap width is 1 μm.

**Figure 8.** Electric field distribution of 5 films structure at \( d = 0.9 \) μm and with different bending radius. (a) \( R = 2 \) cm; (b) \( R = 3 \) cm; (c) \( R = 4 \) cm.
Figure 9 shows the sensitivity of the optical gyroscope with a bending radius of 3 cm using these three ring surface plasmonic waveguides as a function of coupling ratio. When the coupling ratio is greater than 60%, the sensitivity is less than 3 deg/h. Compared with the results in [13], the calculation results show that the waveguide loss is further reduced and the sensitivity is improved. It can be seen that in the multi-gap surface plasmon optical waveguide structure, the loss and the sensitivity of the optical gyro can be improved by selecting a reasonable number of metallic films, the width of the gap and the bending radius.

4. Conclusions

In order to design an optical gyroscope with high detection sensitivity and miniaturization, this paper presents an optical gyro based on a multi-gap vertical ring surface plasmon waveguide structure. Axisymmetric coordinate system and modal analysis method are used to calculate the number of metallic films, the gap width and the bending radius related to different effective index models. What’s more, how to select ring resonator with the best structure to form the optical gyroscope is discussed according to the calculation. The results show that when the coupling ratio exceeds 60%, the sensitivity of the optical gyroscope with the radius of 3 cm, which is composed of surface plasmon optical waveguides with the best number of stripes and gap width is less than 3 deg/h. Compared with the literature [13,14,19], the gap structure can further reduce the loss and improve the sensitivity of the gyroscope. Therefore, the research work in this paper not only lays a foundation for the development of miniaturized integrated optical gyro, but also opens up a larger space for its application in aerospace and other fields.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (NSFC) (No. 61603352), Equipment of Advance Research Field Foundation of China (No. 6140003050110), and the Foundation of the China Scholarship Council (No. 201608140219), Natural Science Foundation of Shanxi Province of China (No. 201801D121163).

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Manuscript Received: Jan. 4, 2019
Accepted: Mar. 4, 2019

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