Influence of single mode fiber bending on fiber optic gyroscope scale factor stability

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Abstract: In fiber optic gyroscope using low-polarization and polarization-maintaining hybrid light path, some single mode fiber components and single mode fiber (SMF) are contained. When SMF bends, the transmitted core-guided mode light and whispering gallery (WG) mode light in SMF interfere with each other, and then affect the transmitted light. A model of the influence of SMF bending on FOG scale factor stability was developed and demonstrated. Simulation and experimental results indicate that the SMF bending can lead to the transmitted light mean wavelength drifting and oscillating under temperature ramping, furthermore leads to FOG scale factor instability. The mean wavelength oscillation amplitude depends on the bending radius.

Key words: fiber optic gyroscope(FOG); single mode fiber(SMF) bending; wavelength; scale factor

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单模光纤弯曲半径对光纤陀螺标度因数稳定性的影响

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摘　要： 在采用低偏和保偏混合光路的混偏光纤陀螺的光学架构中，包含了一些单模光纤元件和单模光纤。当单模光纤发生弯曲时，光纤中传输的纤芯导波模式和单模光纤中的界面反射波模式之间将会发生相互干涉，导致光的传输特性受到影响。提出了单模光纤弯曲对光纤陀螺标度因数稳定性影响的数学模型。仿真和实验结果表明：当温度发生变化时，单模光纤弯曲会导致传输光的中心波长发生漂移和振荡，从而影响光纤陀螺标度因数稳定性。中心波长振荡的振幅与弯曲半径直接相关。

关键词： 光纤陀螺； 单模光纤弯曲； 波长； 标度因数

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0 Introduction

Comparing to all-polarization-maintaining fiber optic gyroscope (FOG) and depolarized FOG, FOG using low-polarization and polarization-maintaining hybrid light path has the advantages of low cost, simplified assembling technology and high production efficiency[1–2]. In the hybrid light path, some single mode fiber components and single mode fibers (SMFs) are contained, such as the pigtail fibers of light source, detector and single mode fiber coupler[3].

In some occasions of FOG light path assembling, the SMF has to be bend with a small radius because of the compact structure requirement, which will affect the FOG performance (including bias and scale factor), especially under the conditions of temperature ramping. L. Faustini derived a SMF bending loss model of transmitted light intensity through the weak-perturbation hypothesis[4]. A. Harris simplified this model based on analyzing the interference between the core-guided mode, and a whispering gallery (WG) mode established by reflection at the buffer-air interface[5–6]. However, both of the above two models only presented the relationship between the bending loss and bending radius. The affect of temperature has not been analyzed. Through introducing the opto-thermal properties of fiber, U. Raikar derived the relationship of the bending loss, bending geometry and the temperature[7–8]. However, all the above analysis focus on the SMF bending loss, while not related to the performance of FOG directly. Meanwhile, the presented bending loss models only refer to single wavelength, while not suit for analyzing a broadened light source.

In this paper, we study the influence of the SMF bending on the FOG performance, especially on the scale factor. Because the FOG scale factor is strongly affected by the light source mean wavelength, our work correspondingly turns to study the influence of SMF bending on the transmitted light wavelength.

1 Model establishment

When SMF bends, electromagnetic radiation is ejected from the core and set up a whispering gallery (WG) mode which propagates in the cladding. Then the WG mode light couples back into the core and interferes with the guided core mode, as shown in Fig.1[5–8].

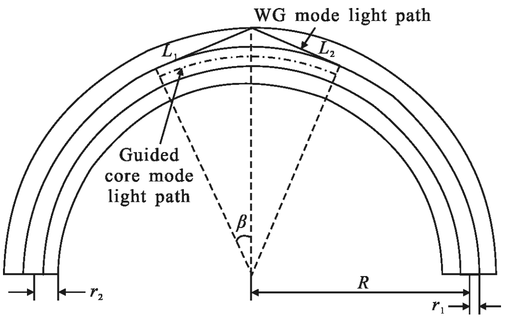


Fig.1 Propagation of light in a bent optical fiber

The SMF bending radius is R, the core radius of the SMF is r_1, and the cladding radius of the SMF is r_2. Hence, the transmitted paths of the WG mode light in the cladding are L_1 and L_2, which can be expressed as:

$$L_1=L_2=[(R+r_2)^2-(R+r_2)^2]^{1/2} \tag{1}$$

and the transmitted light path of guided core mode light is

$$Z=2R\tan^{-1}(L_1/(R+r_1)) \tag{2}$$

When the WG mode light couples back into the core and interferences with the light transmitted in the core, their phase difference is:

$$\varphi_R=\frac{2\pi n_{cl}(L_1+L_2)}{\lambda}-\frac{2\pi n_c z}{\lambda}+\delta \tag{3}$$

where n_c and n_{cl} are the refractive index of fiber core and cladding; λ is the transmitted wavelength; σ is the phase change on reflection (usually it is π)[3].

Referring to[9], for a light source with wavelength around 1 550 nm (the light source with the wavelength locating in this range is usually used in FOG), the bending loss can be obtained with an empirical equation:

$$L=-10\log(I_{out}/I_{in})=5F_1(5F_2+F_3) \tag{4}$$

where L is the bending loss; I_{in} is the input light intensity and I_{out} is the output light intensity from bending fiber. $F_1=c\mathrm{e}^{-R_{\mathrm{eff}}/3}$, $F_2=aJ_1(2.25R_{\mathrm{eff}})$, $F_3=b\mathrm{e}^{-R_{\mathrm{eff}}/5}$ and $a=-1.59$, $b=12.05$, $c=2.79$, $R_{\mathrm{eff}}=R-0.0008$. Suppose the bending loss energy is the intensity of the WG mode light leaked into the cladding, hence we can get $I_{\mathrm{cladding}}=I_{\mathrm{in}}10^{-0.1L}$ from Eq. (4). Correspondingly, the intensity of guide core mode (the light keeps transmitting in fiber core) is $I_{\mathrm{core}}=I_{\mathrm{in}}-I_{\mathrm{cladding}}$. Combing of the Eq.(3), after passing the bending SMF, the light intensity with the wavelength λ can be expressed as:

$$I(R,\lambda)=I_{\mathrm{core}}+I_{\mathrm{cladding}}+2\sqrt{I_{\mathrm{core}}I_{\mathrm{cladding}}}\cos(\varphi_R) \tag{5}$$

In additionally, considering of the factor of temperature, the phase difference φ_T between WG mode light and core guided mode light caused by temperature change can be expressed as[7-8]:

$$\varphi_T=\frac{2\pi T}{\lambda}[(L_1+L_2)(n_b\alpha_b+\beta_b)-Z(n_c\alpha_c+\beta_c)] \tag{6}$$

where n_b is the refractive index of SMF buffer; α_c and α_b are the thermal expansivity of SMF core and buffer; β_c and β_b are the thermo-optic coefficient of SMF core and buffer; T is the temperature change. For the WG mode light transmitted in fiber cladding and buffer, the affect of the temperature on buffer properties is much stronger than the affect on cladding properties[7-8]. Hence, we only give the phase delay caused by buffer in Eq.(6).

By combing of Eqs.(5) and (6), we can obtained the model of the influence of temperature and SMF bending radius on the transmitted light with the wavelength λ:

$$I(R,\lambda,T)=I_{\mathrm{core}}+I_{\mathrm{cladding}}+2\sqrt{I_{\mathrm{core}}I_{\mathrm{cladding}}}\cos(\varphi_T)\cos(\varphi_R) \tag{7}$$

For the associated wavelength spectrum of the broadened light source, Eq.(7) gives the influence of temperature and bending radius on each wavelength component of the spectrum. By integrating the influences of all the wavelength components, we can get the model of the broadened light source mean wavelength λ_m:

$$\lambda_m(R,T)=\frac{\sum_{\lambda_{\min}}^{\lambda_{\max}} I(R,\lambda_i,T)\cdot\lambda_i}{\sum_{\lambda_{\min}}^{\lambda_{\max}} I(R,\lambda_i,T)} \tag{8}$$

where λ_i stands for each wavelength component of the broadened light source; $\lambda_{\max}$ and $\lambda_{\min}$ are the upper and lower bound of the light source spectrum. Hence, the mean wavelength change can be obtained:

$$\Delta\lambda_{\mathrm{ppm}}=MT+\frac{\lambda_c(T)-\overline{\lambda_c(T)}}{\overline{\lambda_c(T)}}\times10^6 \tag{9}$$

where M is the temperature dependence coefficient of light source mean wavelength[10]. It should be noticed that the unit of the mean wavelength change is parts per million (ppm).

For FOG, the influence of the mean wavelength change on scale factor is:

$$\Delta K_{\lambda_m}=\frac{\Delta\lambda_{\mathrm{ppm}}}{\lambda_m}\frac{2\pi LD}{\lambda_m c}\frac{1}{K_mK_c} \tag{10}$$

where ΔK_{λ_m} is the scale factor change caused by the mean wavelength change; L is the fiber length, D is the diameter of fiber loop; c is the speed of light in vacuum; K_c and K_m are the gain of circuit and demodulation. Because the scale factor change is proportional to $\Delta\lambda_{\mathrm{ppm}}$, in the following section, we will analyze the influence of temperature and bending radius on mean wavelength change instead of analyzing the influence on scale factor change.

2 Experiment and discussion

Fig.2 is an illustration of FOG using low-polarization and polarization-maintaining hybrid light path. The pigtail fibers of light source, detector and fiber coupler are SMFs. The pigtail fiber of integrated optical circuit (IOC) waveguide and fiber coil use polarization maintaining fibers. A portion of SM fiber coupler pigtail is winded on a spool to get bending fiber with the radiuses of 1cm and 1.5 cm. In order to

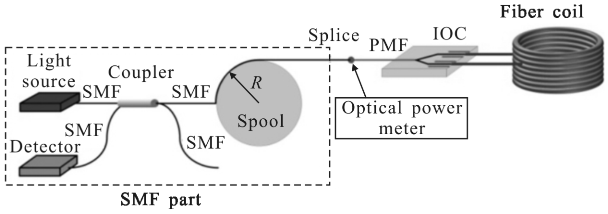
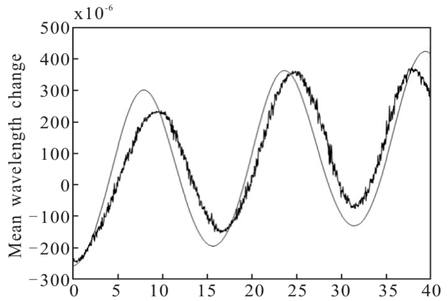


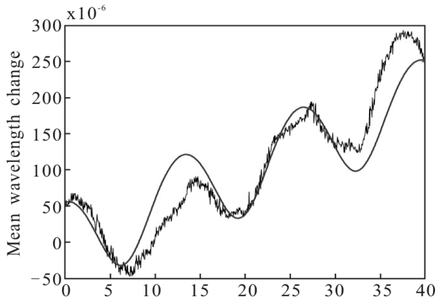
Fig.2 Illustration of FOG using low-polarization and polarization-maintaining hybrid light path

observe the mean wavelength change, we separate the SMF part (the optical path and components at the left of the splice) away from the FOG system and connect with an optical power meter. Put the SMF part into a temperature chamber and set up an environment condition of temperature ramping.

Fig.3 shows the mean wavelength change with different bending radius under temperature ramping from 0 ℃ to 40 ℃. Fig.3 (a) corresponds to the result of bending radius of 1cm, where the red line is the simulation result by using Eq.(9), and the blue line is the experimental result. Fig.3 (b) gives the simulation and experimental results under the bending radius of 1.5 cm. In both figures, the experimental results fit the simulation results very well, which prove our model correct.



(a) Bending radius of 1 cm



(b) Bending radius of 1.5 cm

Fig.3 Mean wavelength change with different bending radiuses under temperature ramping

Furthermore, from Fig.3 we can observe that, the mean wavelength not only increases but also oscillates with the temperature increasing. And the oscillation amplitude relates to SMF bending radius. Fig.4 gives the relationship of the simulated oscillation amplitude and SMF bending radius. Notice that the oscillation amplitude is in logarithmic units. From Fig.4, we can obtain that: (1) The oscillation amplitude decreases with the bending radius increases. It is because that the energy of WG mode light attenuates when the bending radius increases[7]. (2) The logarithmic value of oscillation amplitude is proportional to the bending radius. This conclusion can be used in the FOG design which has strict requirement on scale factor stability. As long as we obtain two mean wavelength oscillation amplitudes at two different bending radiuses, the oscillation amplitude at other bending radius can be predicted. Correspondingly, we can design the proper light path assembling structure and set the optimized bending radius to satisfy the scale factor stability requirement.

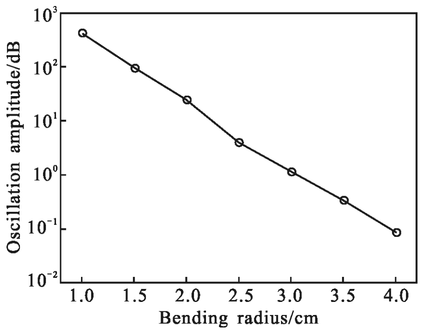


Fig.4 Relationship between oscillation amplitude and bending radius

3 Conclusion

FOG using low-polarization and polarization-maintaining hybrid light path contains some SMF optical components and SMF path. These SMFs bending will influence the FOG performance, especially on the scale factor stability. In this work, we established a model and analyzed the influence of SMF bending and temperature on FOG scale factor. Simulation and experimental results indicate that the SMF bending will lead to the mean wavelength change increasing and oscillating with the temperature increasing, which will also lead to a scale factor oscillating. Smaller bending radius corresponds to larger oscillation amplitude. Based on the simulation result, an optimized bending radius estimation method is proposed.

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