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Sensitivity analysis of a fiber ring resonator based on an air-core photonic-bandgap fiber

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ABSTRACT

The fiber ring resonator (FRR) is the core sensing element in a resonator fiber optic gyroscope (R-FOG), and its sensitivity determines the performance of the R-FOG. This paper presents an in-depth analysis of the sensitivity of the FRR which is made of an air-core photonic-bandgap fiber (PBF), in which the characteristics of the FRR using PBF are compared with that of an FRR using a conventional single mode fiber. When using PBF instead of conventional fiber, it is found that the resonance curve is changed, and the sensitivity of the FRR is decreased a little when a narrow spectral linewidth laser is used. However, the degree of the decrease in sensitivity is not big enough to deny the advantages of PBF in improving the performance of the R-FOG considering that PBF is much better than conventional fiber in reducing the drift. Also, the optimal parameters of the directional coupler for sensitivity are discussed. It is found that the optimal intensity coupling coefficient when using PBF is nearly two times larger than that when using conventional fiber, and the optimal coupler intensity loss when using PBF is smaller than that when using conventional fiber.

1. Introduction

Using the Sagnac effect [1], a resonator fiber optic gyro (R-FOG) has potential as a high accuracy inertial rotation sensor [2]. However, the Rayleigh backscattering [3,4], the Kerr [5,6], Faraday [7,8] and thermal effects [9,10] generally limit the accuracy of the R-FOG. Air-core photonic-bandgap fiber (PBF) is a new kind of fiber [11,12]. Since the optical mode is mostly confined to the air-core when the light travels in the air-core PBF, the four effects in an air-core PBF would be smaller than that in a conventional fiber [11,13]. Therefore, in order to improve the performance of the interference fiber optic gyro (I-FOG), Kim et al. have proposed an I-FOG based on an air-core PBF [13]. The air-core PBF could be used in the R-FOG to improve its performance also; therefore, it is meaningful to study the R-FOG based on an air-core PBF [14,15].

The fiber ring resonator (FRR) is the core sensing element in the R-FOG [16]. The sensitivity of the FRR plays a large role in determining the performance of the R-FOG [17,18]. The analysis of the sensitivity has been done for a FRR using a conventional single mode fiber [17]; however, an in-depth analysis of an FRR based on an air-core PBF has not been done. The characteristic parameters (such as the refractive index and the attenuation loss of the fiber) of the air-core PBF and the conventional fiber are very different, and this would lead to the resonance characteristics of the FRR with different fibers to be different, which would finally give rise to the difference in the sensitivities [1,17]. This paper discusses the sensitivity of a FRR based on an air-core PBF, and a comparison of the sensitivities which occur upon the use of an air-core PBF and conventional fiber are presented. Finally, the optimal parameters of the directional coupler to achieve optimal sensitivity are compared when using PBF and conventional fiber.

2. Theory

Fig. 1 illustrates the configuration of the FRR based on an air-core PBF of length L [16]. The input electric field E_{in} is divided into two parts: one part named E_{FRR} is coupled into the FRR through the directional coupler, and is output from the FRR after circulating in the FRR; and the other part named E_{through} is transmitted through the directional coupler directly. Finally, the interference between E_{through} and E_{FRR} happens at the output port of the directional coupler. In this paper, when we analyze the FRR using PBF, the directional coupler is assumed to be made of air-core PBF also; and when we analyze the FRR using conventional fiber, the directional coupler is assumed to be made of conventional single mode fiber also. Therefore, the large fusion-splice loss between PBF and conventional fiber does not have to be considered. The input electric field E_{in} can be written as [5,17]:

$$E_{in}(t) = E_0 \exp\{i[2\pi f_0 t + \varphi(t)]\} \quad (1)$$

where E_0 is the amplitude of the electric field of the laser light, and f_0 is the center frequency of the laser. The phase fluctuation $\varphi(t)$

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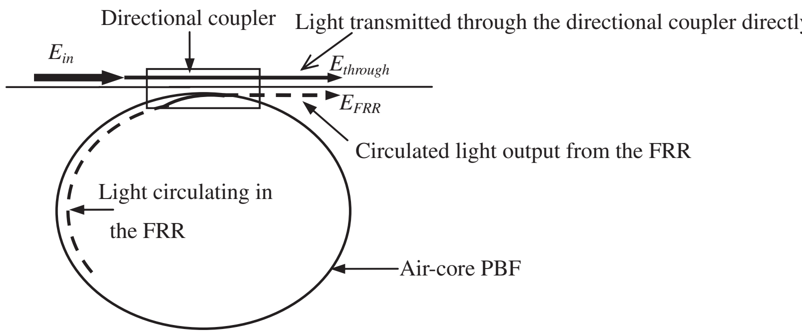

Fig. 1. Configuration of the FRR based on an air-core PBF.

represents the important parameter of optical source coherence [5], and it satisfies [17,19]:

$$\langle \exp(i\varphi(t))\exp(-i\varphi(t-\tau))\rangle = \exp(-\pi\delta f\tau), \quad \tau > 0 \tag{2}$$

where δf is the spectral linewidth of the laser, and τ is the time delay. The output intensity of the FRR normalized by the input intensity can be derived as [17,20]:

$$T_{\mathrm{FRR}} = (1-\alpha_C)\left[1-\rho\frac{(1-Q)^2}{(1-Q)^2+4Q\sin^2(\pi\cdot\Delta f\tau_0)}\right] \tag{3}$$

where α_C is the intensity loss of the directional coupler; $\Delta f = f_0 - f_R$ is the resonance frequency deviation, f_R is the resonance frequency of the FRR; $\tau_0 = n_r L/c$ is the transit time in the FRR, n_r is the refractive index of the fiber and c is the light velocity in vacuum; and other parameters can be written as [20,21]:

$$\rho = 1-\frac{1}{1-\alpha_C}\cdot\left[T^2-\frac{2TR}{1-Q}+\frac{(R')^2}{1-(Q')^2}\cdot\frac{1+Q}{1-Q}\right] \tag{4a}$$

$$T = \sqrt{1-k_C}\cdot\sqrt{1-\alpha_C} \tag{4b}$$

$$R' = k_C\cdot(1-\alpha_C)\cdot\exp(-\alpha_L L/2), \quad R = R'\exp(-\pi\delta f\tau_0) \tag{4c}$$

$$Q' = \exp(-\alpha_L L/2)\cdot\sqrt{1-k_C}\cdot\sqrt{1-\alpha_C}, \quad Q = Q'\exp(-\pi\delta f\tau_0) \tag{4d}$$

where k_C is the intensity coupling coefficient of the directional coupler, and α_L is the fiber attenuation loss in the FRR.

From Eq. (3), the characteristic parameters of the resonance curve can be obtained. The linewidth of the resonance curve can be derived as [17]:

$$\Gamma = \frac{\cos^{-1}\left\{\frac{2TRQ[1-(Q')^2]-2(R')^2Q^2}{(TRQ^2+TR)\cdot[1-(Q')^2]-(R')^2Q(1+Q^2)}\right\}}{\tau_0\pi} \tag{5}$$

And the maximum and minimum of the resonance curve can be derived as [17]:

$$T_{\mathrm{FRR\_max}} = T^2+\frac{2TR}{1+Q}+\frac{(R')^2}{1-(Q')^2}\cdot\frac{1-Q}{1+Q} \tag{6}$$

$$T_{\mathrm{FRR\_min}} = T^2-\frac{2TR}{1-Q}+\frac{(R')^2}{1-(Q')^2}\cdot\frac{1+Q}{1-Q} \tag{7}$$

According to Eqs. (5)–(7), the linewidth, maximum and minimum of the resonance curve are dependent on the characteristic parameters of the fiber. Since the refractive index n_r and fiber attenuation loss α_L of the PBF and conventional fiber are different, the resonance characteristics of the FRR when using air-core PBF and conventional fiber would also be different.

The sensitivity of the FRR is an important parameter of the R-FOG, which can be written as [1,10,17]:

$$\delta\Omega \approx \frac{\lambda P}{4A}\frac{\sqrt{2}\Gamma}{\mathrm{SNR}} \tag{8}$$

where λ is the wavelength of the laser, P is the perimeter of the FRR, A is the area enclosed by the FRR, and SNR is the signal-to-noise ratio of the system. The shot noise limited SNR can be written as [17]:

$$\mathrm{SNR} = \sqrt{\frac{\eta t_0 I_0}{2hf_0}}\frac{T_{\mathrm{FRR\_max}}-T_{\mathrm{FRR\_min}}}{\sqrt{T_{\mathrm{FRR\_max}}}} \tag{9}$$

where η is the photo-detector quantum efficiency, t_0 is the integration time, $I_0 = E_0^2$ is the intensity of the laser at input of the coupler, and h is Planck's constant. Since the sensitivity is a function of the resonance characteristic parameters, and the resonance characteristics are dependent on the type of fiber employed, the sensitivities corresponding to PBF and conventional fiber would be different [1,17]. Also, the sensitivity depends on the parameters of the directional coupler k_C and α_C, therefore, the relationship between the sensitivity, the fiber and the directional coupler parameters will now be looked at closely in order to optimize the characteristics of the FRR.

3. Simulation and discussion

Fig. 2 illustrates the resonance curve when using air-core PBF or conventional fiber. The parameters are assumed to be as follows: the intensity I_0 at the input of the FRR is 1mW, the wavelength of the laser λ is 1550 nm, the spectral linewidth of the laser δf is 60 kHz, the diameter D of the FRR is 0.1 m, the fiber length L of the FRR is 20 m, the effective refractive index n_r is 0.99 for PBF and 1.45 for conventional fiber, the intensity coupling coefficient k_C is 5%, the coupler intensity loss α_C is 6.67%, and the fiber attenuation loss α_L is 20 dB/km for PBF and 0.2 dB/km for conventional fiber [2,14,22]. Comparing the resonance curve when using air-core PBF with that when using conventional fiber, it is obvious that some characteristics of the two resonance curves are different: firstly, the minimum of the resonance curve using air-core PBF is slightly larger than that using conventional fiber; secondly, the linewidth of the resonance curve using air-core PBF is slightly larger than that using conventional fiber.

Fig. 3 illustrates the relationship between the sensitivity $\delta\Omega$ and the spectral linewidth of the laser δf when using air-core PBF or conventional fiber. The parameters are as follows: the photo-detector quantum efficiency η is 0.8, the integration time t_0 is 1s [5], and other parameters are the same as aforementioned. It is shown in Fig. 3 that the FRR becomes less sensitive as the spectral linewidth of the laser increases. Especially, it is found that the sensitivity using air-core PBF is better than that using conventional fiber only if the linewidth is above a certain value, which is about 600 kHz in