Optics Communications 387 (2017) 18–23

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Optimization of the sinusoidal phase modulation technique in resonant fiber optic gyro

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ARTICLE INFO

Keywords:
Resonant fiber optic gyro
Sagnac effect
Phase modulation technique

ABSTRACT

The sinusoidal wave phase modulation and demodulation have been widely used in the signal processing system of the resonant fiber optic gyro (RFOG). An appropriate selection of the modulation frequency is of great importance, for the frequency value directly affects the slope of the demodulation curve at the resonance point which carries the gyro output information. A large demodulation slope is pursued in a high-performance RFOG. In this paper, an analytical expression of the demodulation slope is for the first time deduced in both transmission-type and reflection-type fiber ring resonators without any approximation. The relationship between the slope value and the modulation frequency at the resonance point is accurately calculated. The calculated best modulation frequency maximizing the demodulation slope at the resonance point is different from previous widely used optimal frequency given by the Lorentzian approximation method. More importantly, both theoretical and experimental results indicate that the achieved maximal demodulation slope from the proposed analytical expression method is double of that obtaining from the Lorentzian approximation method.

1. Introduction

The gyro is an inertial sensor for the measurement of the rotation rate. The resonant fiber optic gyro (RFOG) based on the Sagnac effect has the advantages of good resistance, high sensitivity and large dynamic range [1]. Compared with the traditional interferometric fiber optic gyro (IFOG), the RFOG has the potential to achieve a same detection precision with much shorter fiber length, which gives obvious superiority in the further miniaturization and integration as well as improves its application value in the field of navigation and guidance systems [1–3].

The key element of the RFOG is a fiber ring resonator (FRR), and its main function is the enhancement of the Sagnac effect thanks to the multiple transmissions of the light in the cavity. However, the frequency difference introduced by the Sagnac effect which indicates the actual rotation rate is still too weak to be detected out on a laser central frequency of about 194 THz, if the to-be-tested angular velocity is 1 °/h and the corresponding frequency difference is less than 1 Hz, for an FRR with a diameter of 10 cm. What's more, the environmental temperature change exerts severe impact on the laser central frequency and the resonant frequency of the FRR. A temperature fluctuation of 1 °C results in a resonant frequency drift as high as GHz. Thus, the modulation and demodulation technique is necessary for the improvement of the system detecting sensitivity. The phase modulation technique is widely used in the RFOG which includes sinusoidal wave modulation [4,5], triangular wave modulation [6], sawtooth wave modulation [7] and various hybrid modulations [8]. The most widely used technique is the sinusoidal wave phase modulation and demodulation.

Although the RFOG detection precision is affected by various optical noises, such as the backscattering noise [9,10], the polarization fluctuation [11–14] and the optical Kerr effect [15], the theoretical sensitivity of the RFOG and the signal-to-noise ratio (SNR) of the detection system are limited to the slope of the demodulation curve at the resonance point which carries the gyro output information. A larger demodulation slope is pursued in a high-performance RFOG. In the sinusoidal wave phase modulation technique, once the structure parameters of the FRR are confirmed, the frequency value of the sinusoidal wave determines the slope of the demodulation curve at the resonance point.

Since the selection of the modulation frequency in the RFOG is of great importance, many calculation methods have been proposed to choose the best frequency which maximizes the demodulation slope at the resonance point. The Lorentzian approximation method has been widely adopted in the calculation of the best modulation frequency [16–18]. The optical intensity transfer function of the FRR is approxi-

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http://dx.doi.org/10.1016/j.optcom.2016.11.025
Received 2 September 2016; Received in revised form 10 November 2016; Accepted 13 November 2016
0030-4018/

mated to a Lorentzian lineshape, and the optimal modulation frequency is solved to be $\Gamma_c/2\sqrt{3}$ where Γ_c is the linewidth of the resonant curve of the FRR [16,17]. Although it is well known that the actual resonant curve of the FRR is different from the Lorentzian lineshape, the result of the Lorentzian approximation method is commonly used in the RFOG system thanks to its simplicity and convenience. However, experiments have proved that the Lorentzian approximation has its limitation and is not precise enough, for the actual slope value does not reach to its maximum while the modulation frequency is set to be $\Gamma_c/2\sqrt{3}$. In this paper, the analytical expression of the demodulation slope at the resonance point is for the first time deduced without any approximation, and the relationship between the slope value and the modulation frequency is accurately calculated. The calculated best modulation frequency is experimentally verified to maximize the demodulation slope, which is double of that while the modulation frequency is $\Gamma_c/2\sqrt{3}$. An RFOG system is established, and the gyro lock-in accuracy is also demonstrated to be improved by a factor with the best modulation frequency obtained from the analytical expression.

2. Sinusoidal phase modulation technique

The system block diagram of the open-loop RFOG based on the sinusoidal wave phase modulation technique is depicted in Fig. 1. The lightwave from the laser is divided into two equivalent beams after the coupler C0, and then the two beams are incident to the FRR through the phase modulators, PM1 and PM2, in clockwise (CW) and counter-clockwise (CCW) directions, respectively. The CCW lightwave is demodulated by the lock-in amplifier (LIA), LIA2, and is fed back to the laser tuning end through a servo controller to stabilize the laser central frequency. The CW lightwave is demodulated by LIA1 and output as the gyro signal. The sinusoidal waves applied on PM1 and PM2 have different frequencies, f_1 and f_2, in order to reduce the negative impact of the backscattering noise [9]. The modulation amplitude V_1 and V_2 should be set to suppress the carrier at the most extent [9].

Fig. 2 shows the sinusoidal wave phase modulation and demodulation of a transmission-type FRR. Fig. 2(a) shows the resonant curve of the FRR and the sinusoidal wave phase modulation process, where f_q is the q-order resonance frequency of the FRR and q is an integer. When the laser central frequency f keeps consistent with the resonance frequency of the FRR f_q, the output of the photodetector (PD) is an ideal 2nd harmonic signal of the modulating signal and the demodulation output is zero, as shown in Fig. 2(b). While there is a frequency deviation Δf between the laser central frequency and the resonance frequency of the FRR, the output of the PD contains the 1st harmonic of the modulating signal as shown in Fig. 2(a), and the demodulation output has a linear relationship with the frequency deviation as shown in Fig. 2(b). The demodulation curve is centrosymmetric to the resonance frequency f_q near which there is a linear range. When the slope at the resonance point is bigger, the corresponding frequency shift induced by a slight rotation is larger and easier to be detected. Thus the demodulation slope directly determines the gyro sensitivity.

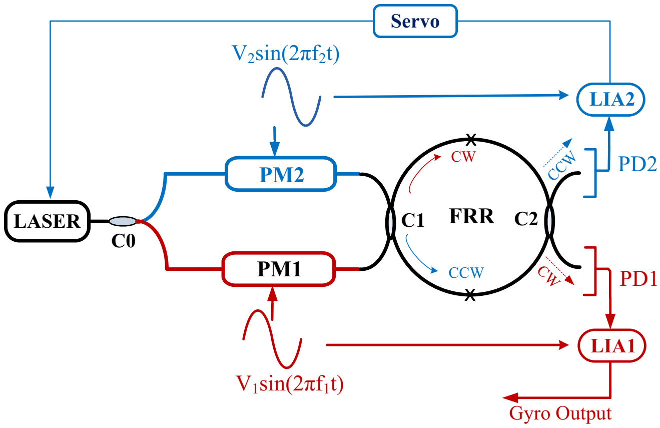

Fig. 1. System block diagram of the open-loop RFOG.

Fig. 3 shows the calculated normalized resonant curves near each resonance mode of the transmission-type FRR quipped in the practical RFOG. Fig. 3(a) is the accurate practical resonant curve. In Fig. 3(b), the amplitude is assumed to exhibit a Lorentzian lineshape as [18]

$$T(f) = \frac{\Gamma_c^2}{\Gamma_c^2 + (f - f_0)^2} \tag{1}$$

which is derived as the limit for Γ_c«FSR of the periodic lineshape of the FRR. The free spectral range (FSR) of the FRR is related to its fiber length L and refractive index of the fiber n_r by FSR=c/$n_r L$. c is the light velocity. The Lorentz approximation gives the analytical expression of the relationship between the demodulation slope and the modulation frequency, and calculates the optimal modulation frequency to be $\Gamma_c/2\sqrt{3}$. Since the finesse F=FSR/Γ_c reflects the loss of the FRR, a higher finesse improves the theoretical sensitivity of the RFOG. However in the practical RFOG, special design of the FRR is necessary. For instance, single-polarization fibers [19] or polarizers [20] are inserted to the FRR to reduce the polarization fluctuation noise, which makes the finesse of the FRR lower, generally 15–30. Therefore, the aforementioned condition of the Lorentz approximation Γ_c« FSR is not available yet. In the simulated resonant curve shown in Fig. 3, the structure parameters of the FRR is as follows: the linewidth Γ_c is 334 kHz., the refractive index of the fiber n_r is about 1.45 and the fiber length L is 21.2 m, so that the FSR is equal to 9.72 MHz. It is obviously inappropriate to assume $\Gamma_c \ll$FSR and adopt the Lorentzian lineshape to optimize the modulation frequency. The simulation result of the demodulation curves under different modulation frequencies proves the inapplicability of the Lorentz approximation method, as shown in Fig. 4.

Based on the accurate practical resonant curve shown in Fig. 3(a), Fig. 4 shows the simulation result of the demodulation curves under three different modulation frequencies of 50 kHz, 96.4 kHz, and 160 kHz, among which 96.4 kHz is the optimal modulation frequency calculated by Lorentzian approximation [16,17]. The demodulation output is equivalent to voltage values for the demodulation is processed in the field programmable gate array (FPGA) and the output is an electrical signal. However, the slope of demodulation curve at the resonance point (Δf=0) reaches to its maximum when the modulation frequency is 50 kHz, depicted in the red line. When the modulation frequency is set to be 96.4 kHz, the corresponding demodulation curve depicted in the black line has a maximal peak-to-peak value, but not a maximal slope at the resonance point. Therefore, the widely adopted Lorentzian approximation method is not precise enough to calculate the optimal modulation frequency. A more scientific and accurate method is necessary for the selection of the optimal modulation frequency instead of the Lorentzian approximation.

3. Optimization of the modulation frequency

3.1. Transmission-type FRR

The output signal light of a narrow linewidth laser E_{laser} is expressed as

$$E_{laser} = E_0 \exp(j\cdot 2\pi f t) \tag{2}$$

where E_O is the light field amplitude of the laser, and f is the laser central frequency. The Fourier expansion of the light field after the phase modulator is simplified as [21]

$$E_{PM} = E_0 \sum_{n=-\infty}^{\infty} J_n(M) expj(2\pi f t + n\cdot 2\pi f_M t) \tag{3}$$