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Double closed-loop control of integrated optical resonance gyroscope with mean-square exponential stability

HUI LI,[1,2,*] LIYING LIU,[1,2] ZHILI LIN,[3] QIWEI WANG,[1,2] XIAO WANG,[1,2] AND LISHUANG FENG[1,2]

[1]*Key Laboratory of Precision Opto-mechatronics Technology (Ministry of Education), Beihang University, Beijing 100191, China*
[2] *Key Laboratory of Micro-nano Measurement-Manipulation and Physics (Ministry of Education), Beihang University, Beijing 100191, China*
[3]*College of Information Science and Engineering, Huaqiao University, Xiamen 361021, China*
**lihui@buaa.edu.cn*

Abstract: A new double closed-loop control system with mean-square exponential stability is firstly proposed to optimize the detection accuracy and dynamic response characteristic of the integrated optical resonance gyroscope (IORG). The influence mechanism of optical nonlinear effects on system detection sensitivity is investigated to optimize the demodulation gain, the maximum sensitivity and the linear work region of a gyro system. Especially, we analyze the effect of optical parameter fluctuation on the parameter uncertainty of system, and investigate the influence principle of laser locking-frequency noise on the closed-loop detection accuracy of angular velocity. The stochastic disturbance model of double closed-loop IORG is established that takes the unfavorable factors such as optical effect nonlinearity, disturbed disturbance, optical parameter fluctuation and unavoidable system noise into consideration. A robust control algorithm is also designed to guarantee the mean-square exponential stability of system with a prescribed H_∞ performance in order to improve the detection accuracy and dynamic performance of IORG. The conducted experiment results demonstrate that the IORG has a dynamic response time less than 76us, a long-term bias stability 7.04°/h with an integration time of 10s over one-hour test, and the corresponding bias stability 1.841°/h based on Allan deviation, which validate the effectiveness and usefulness of the proposed detection scheme.

OCIS codes: (120.5790) Sagnac effect; (060.2800) Gyroscopes; (060.2370) Fiber optics sensors.

References and links

1. C. Ciminelli, F. Dell'Olio, C. E. Campanella, and M. N. Armenise, "Photonic technologies for angular velocity sensing," Adv. Opt. Photonics **2**(3), 370–404 (2010).
2. J. Haavisto and G. A. Pajer, "Resonance effects in low-loss ring waveguides," Opt. Lett. **5**(12), 510–512 (1980).
3. M. Á. Guillén-Torres, E. Cretu, N. A. F. Jaeger, and L. Chrostowski, "Ring resonator optical gyroscopes-Parameter optimization and robustness analysis," J. Lightwave Technol. **30**(12), 1802–1817 (2012).
4. N. Barbour, "Inertial Navigation Sensors [R]," Charles Stark Draper Lab Inc Cambridge ME, 2010.
5. N. Barbour and G. Schmidt, "Inertial sensor technology trends," IEEE Sensors **1**(4), 332–339 (2001).
6. W. Liang, V. S. Ilchenko, A. A. Savchenkov, E. Dale, D. Eliyahu, A. B. Matsko, and L. Maleki, "Resonant micro photonic gyroscope," Optica **4**(1), 114–117 (2017).
7. J. Wang, L. Feng, Y. Tang, and Y. Zhi, "Resonator integrated optic gyro employing trapezoidal phase modulation technique," Opt. Lett. **40**(2), 155–158 (2015).
8. X. Wang, Z. He, and K. Hotate, "Reduction of polarization-fluctuation induced drift in resonator fiber optic gyro by a resonator with twin 90 ° polarization-axis rotated splices," Opt. Express **18**(2), 1677–1683 (2010).
9. J. I. Thorpe, K. Numata, and J. Livas, "Laser frequency stabilization and control through offset sideband locking to optical cavities," Opt. Express **16**(20), 15980–15990 (2008).
10. K. Hotate and M. Harumoto, "Resonator fiber optic gyro using digital serrodyne modulation," J. Lightwave Technol. **15**(3), 466–473 (1997).
11. M. Lei, L. Feng, Y. Zhi, and H. Liu, "Effect of intensity variation of laser in resonator integrated optic gyro," Appl. Opt. **52**(19), 4576–4581 (2013).

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Analysis on the Optimization of High-Frequency Performance for Optical Voltage Sensors Based on Pockels Effect

Liying Liu, Hui Li, *Member, IEEE*, Zhida Fu, and Lishuang Feng

***Abstract*— A novel closed-loop signal detection method is proposed to optimize the high-frequency performance of the optical voltage sensors (OVSs) based on Pockels effect. First, a timing sequence control method is introduced to accomplish the whole closed-loop process within one transit period of the optical propagation path, which can ensure the system high dynamic response with high-frequency signal input. Then, we investigate the frequency spectrum of closed-loop error, and design the signal processing before the closed-loop controller with a low pass filter to enhance the signal to noise ratio without reducing the system bandwidth. Furthermore, considering the optical parameter uncertainty and the unavoidable external disturbance, a closed-loop control algorithm is presented to optimize the steady state accuracy and dynamic performance of OVSs. The experimental results show that the closed-loop steady state accuracy of sine response, slope response, and acceleration measurement with the 20-kHz input signal are basically consistent with the static accuracy, and the relative measurement error of OVS is ±0.1% with the applied voltage over 100 V, which verify the effectiveness of the proposed detection scheme.**

***Index Terms*—Optical voltage sensor, signal detection, detection precision.**

I. INTRODUCTION

AS AN important component in electrical power transmission and distribution system, optical voltage sensors (OVSs) have been continuously researched as the suitable candidate [1] for high voltage measurement due to its inherent merits such as small size, electromagnetic insulation, wide bandwidth and the low cost [2], [3]. Recently, much work has been devoted to the signal detection method of OVS based on Pockels effect [4], which is crucial to achieve a precise and reliable voltage sensing compared with other conventional voltage sensors [5].

A compensation scheme of OVS based on Bi4Ge3O12 (BGO) crystal was proposed to eliminate the effects of temperature-dependent birefringence and pressure-induced birefringence, which improves the disturbance rejection attenuation level of OVS [6]. Then, this configuration was applied in the practical 115 kV~550kV OVSs by Asea Brown Boveri Limited Company (ABB) [7], [8]. Li and Zeng [9] presented an effective method to remove the additional quarter wave-plate and simplify the sensing system by a single Fresnel rhomb BGO crystal. A signal processing scheme with two bulk BGO crystals was proposed to counteract the birefringence without dependency on the match of two optical paths [10]. However, all these systems are open-loop signal processing methods [6]–[10], which are difficult to suppress the nonlinearity between the interference light intensity and output voltage. Recently, the digital closed-loop signal detection technology has been introduced to optimize the OVS performance.

Zhang *et al.* [11] demonstrated a quasi-reciprocal reflective OVS adopting the closed-loop detection technology in fiber optical gyroscope. Li *et al.* [12] presented a main closed-loop to restrain the signal intensity fluctuation [12] and a second closed-loop to compensate the gain drift of the optical phase modulator (OPM) [13], which improve the OVS robustness and consequently obtain a wide dynamic range and good linearity. A control algorithm was further put forward to suppress the stochastic disturbance and improve the static detection accuracy in low voltage measurement [14]. Then, they optimized the loop gain and designed a hardware circuit to improve the system signal to noise ratio (SNR) and the dynamic tracking performance [15].

Although the system dynamic tracking ability and static measurement precision have been improved in the previous literatures, we noticed that the steady state accuracy with high frequency voltage still remains an issue, which is difficult to improve through only hardware circuit [15]. Further, the closed-loop error signal is a weak signal containing strong white noise, thus it is of great significance to accurately extract the closed-loop error based on the frequency spectrum without affecting the fast tracking ability of the system, which is neglected in the related research [11]–[15].

In order to solve these problems, in this paper, a novel closed-loop signal detection method is proposed to optimize the high frequency performance of OVSs based on Pockels effect. First, a timing sequence control method is presented to complete the closed-loop process within one transit period of the optical propagation path. Then, the signal processor before the controller with a low pass filter is designed based on the frequency spectrum of closed-loop error, which can improve the SNR and guarantee the bandwidth of OVS.

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The authors are with the Department of Electro-Optical Engineering, School of Instrument Science and Optoelectronics Engineering, Beihang University, Beijing 100191, China (e-mail: xiaocuter@hotmail.com; lihui@buaa.edu.cn; fuzhida@buaa.edu.cn; fenglishuang@buaa.edu.cn).

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