中国激光

光纤陀螺空间应用技术

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摘要 光纤陀螺已成为航天器惯性导航与姿轨控制的主选器件。经过几十年的技术攻关，北京航空航天大学形成了成熟的光纤陀螺技术体系，研制了适用于各种空间应用需求的光纤陀螺系列产品。对北京航空航天大学光纤陀螺空间应用的若干关键技术加以综述。基于高可靠和小型化要求，介绍了双光源四轴光纤陀螺方案，阐述了光纤陀螺在轨故障诊断技术；为进一步实现小型化，介绍了小型三轴一体光纤陀螺配置方案以及利用时分复用技术实现的最简三轴陀螺配置方案；介绍了进一步提高组件级抗辐照性能的基于保偏光子晶体光纤的光纤陀螺方案。基于上述关键技术和配置方案的系列光纤陀螺产品，已在数十次空间任务中发挥了重要作用。

关键词 光纤光学；光纤陀螺；空间应用；在轨诊断；时分复用；光子晶体光纤
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1 引 言

干涉式光纤陀螺(IFOG)是基于 Sagnac 效应的角速度惯性敏感器件。IFOG 以其全固态、抗辐照、低能耗、高动态性能、长寿命等优势已经成为航天器惯性导航和姿轨控制的主选器件[1-2]。

近年来，空间战略部署被认为是提升国家和地区军事实力的重要手段，卫星技术随之迅速发展，特别是在低轨、小型化和高通量卫星技术上取得的成就最为突出。根据 Union Concerned Scientists (UCS) 卫星数据库显示，截至 2022 年 1 月 1 日，4852 颗卫星正在地球轨道上运行，其中 511 颗所属为中国[3]。卫星技术的发展对空间用光纤陀螺提出了新的要求。一方面是高可靠技术。在卫星故障分析中，姿态与轨道控制分系统的故障率一直处于高位[4]。作为姿态与轨道控制分系统的核心部件，在光纤陀螺设计过程中，保证可靠性应始终放在首位。从发射过程中的高强度振动，到入轨后银河宇宙辐射、高能粒子、热真空等，这些复杂恶劣的空间工作环境要求光纤陀螺必须在对抗外部扰动、提升环境适应性方面做足准备[2,5-6]。特别是在高轨道、高倾角和深空作业环境下，空间粒子的能量、剂量率、辐射累积总剂量大幅升高，因此，提升光纤陀螺组件的抗辐照性能至关重要。另一方面是小型化技术。在保证寿命和性能的同时，更低功耗、更轻质量和更少成本的单机显然是更优的选择，尤其是应用在微纳卫星时，单机的可利用资源将进一步受限，因此，对光纤陀螺小型化技术手段进行研究，是光纤陀螺在中低精度应用领域上提升竞争力的必要环节。

目前，欧美国家工业部门的光纤陀螺产品已批量应用于空间领域，法国的 iXblue 公司、美国的 Northrop Grumman 公司和 Honeywell 公司、俄罗斯的 Optolink 公司和 Fizoptika 公司等在空间用光纤陀螺的研制和应用上拥有着丰富的经验[2]。光纤陀螺产品也凭借不断的小型化和环境适应性改进，正在越来越多地应用于各类小型空间飞行器[7-8]。

近年来，国内光纤陀螺水平也随着相关技术的发展得到了快速提升，光纤陀螺在越来越多的空间任务中发挥着作用，如“天宫一号”、“神舟”系列飞船、“嫦娥”系列月球探测器以及多个型号在轨卫星均应用了光纤陀螺作为姿态与轨道控制分系统的核心惯性敏感器。经过多年的攻关，北京航空航天大学从高可靠、小型化两条路线出发，在空间用光纤陀螺的结构配置优化、检测技术创新、功能密度提升、器件优化升级等关键技术上接连取得重大突破，研制的多个空间用光纤陀螺型号产品已在超过 60 颗卫星上稳定工作。

基于空间应用的高可靠和小型化需求，本文介绍了小型四轴双光源光纤陀螺方案，相比于传统独立六轴冗余方案，在实现组件双重备份的同时，该方案在质量、尺寸和功耗上拥有巨大优势。同时阐述了提高陀螺组件可靠性的故障诊断技术，全数字化的实现未带来任何额外的成本。为进一步实现小型化，介绍了小型三轴一体光纤陀螺配置方案以及利用时分复用(TDM)技术实现的最简三轴陀螺配置方案。介绍了保偏光子晶体光纤陀螺方案，可以实现光纤陀螺组件级抗辐照性能的大量提升。最后，介绍了北京航空航天大学研制的高可靠、小型化、耐辐照的典型空间用光

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纤陀螺系列产品。

2 空间用光纤陀螺技术

2.1 高可靠技术

典型的数字闭环干涉式光纤陀螺由光源、耦合器、集成光学芯片(IOC)、光纤环、光电探测器和信号处理电路构成。图 1 为单轴干涉式光纤陀螺结构示意图。IOC 和光纤环组成了 Sagnac 干涉仪的敏感环路,用于传感转速信息。当惯性空间的转速在干涉仪敏感环路的轴向分量为 Ω 时,敏感环路中相向传播的两束光之间会产生相位差 $\Delta\varphi_s$[1]。根据 Sagnac 效应,相位差与输入转速之间的关系可以表示为

$$\Delta\varphi_s=\frac{2\pi LD}{\lambda c}\Omega, \tag{1}$$

式中:D 和 L 分别为敏感环路的直径和光纤长度;λ 为光波长;c 为光速。

敏感环路中相向传播的两束光在 IOC 的单端口干涉输出,探测器将干涉光信号转换为电信号,最终在信号处理电路中解调输出转速值。通过在 IOC 上施加负反馈信号,实现干涉相位工作点的闭环控制[9]。

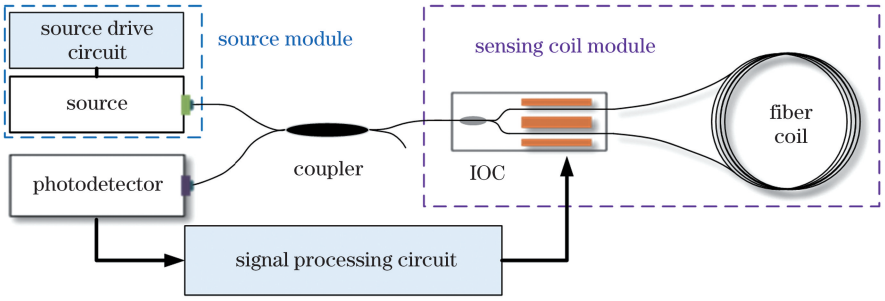

图 1 单轴干涉式光纤陀螺结构示意图

Fig. 1 Diagram of single axis IFOG

然而,光源、光电探测器、光纤环与信号处理电路容易受到辐射、温度等空间环境的影响。表 1 列出了光纤陀螺各组成部分在空间环境下的故障模式与故障发生率[10-11]。

表 1 器件故障模式与故障率

Table 1 Failure modes and failure rates of components

Component	Failure modes	Failure rates /(10^{-6} h^{-1})
Source	Radiation damage, overheating, and outgassing: diode output power falling off, spectrum degraded	6.64
Photodetector	Radiation damage and outgassing: degradation of detection, decrease of photodiode responsivity	3.08
Coupler	Radiation induced attenuation: transmitted light power falling off	0.25
IOC	Radiation induced attenuation: decrease of transmitted light power; propagation of $LiNbO_3$ crystal microfractures, no power transmitted	0.56
Fiber coil	Radiation induced attenuation: power transmitted falling off; fiber broken under the strain: no power transmitted	4.35
Electronics	Space environment damage: latching of the logical device, performance degradation of chips	–

为提高光纤陀螺的可靠性,图 2 所示六轴冗余配置是一种较为传统的设计方案,该方案实现了对全部光电器件的备份,消除了组件的单点失效。然而,这样简单的冗余缺乏针对性,在提高可靠性的同时牺牲了质量功耗的成倍增长,限制了光纤陀螺在卫星上的应用。为解决该问题,共享双光源的四轴光纤陀螺配置方案在节省两轴陀螺的同时,依然能够实现对全部器件的双重备份。如图 3 所示,该配置由两个光源模块和四轴光纤陀螺组成。两个光源模块包含独立的光源与驱动电路,通过两个 1×4 耦合器分别与四轴光纤陀螺相连,每轴陀螺包含独立的光路和信号处理电路,整体利用一套控制电路实现接口通信、状态监控、故障诊断和恢复控制。X、Y、Z 轴陀螺相互正交设置,用于传感 X、Y、Z 三个方向的角速度,冗余的 S 轴按照一定角度倾斜设置,当其他三轴陀螺中任意一轴出现故障时,将启用 S 轴作为替代。当主光源模块故障时,将启用第二光源模块作为替代。与传统的独立六轴冗余配置相比,该方案减少了两轴备份陀螺与四个光源模块,使组件的质量、功耗和包络尺寸大大降低。

备份组件的切换依赖于光纤陀螺的实时状态监控与故障诊断。利用基于光功率和温度参数的纯软件、全数字的在轨实时监测方法[12-13],光纤陀螺的在轨故障诊断可以通过监测在轨随机游走系数实现。首先,对于空间用光纤陀螺,其随机游走系数可由下式估算:

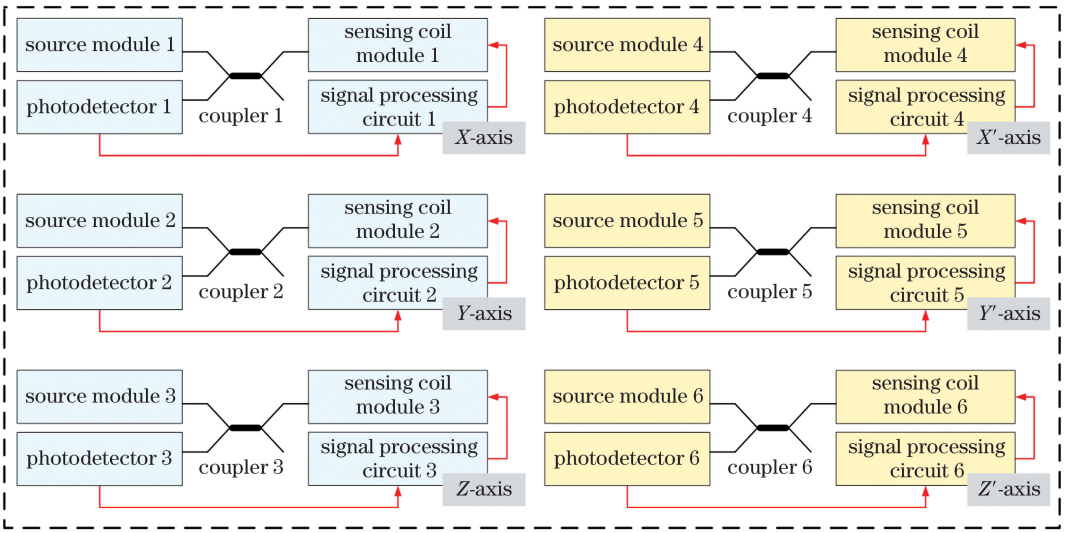

图 2 独立六轴光纤陀螺配置

Fig. 2 Configuration of six-independent-axis IFOG

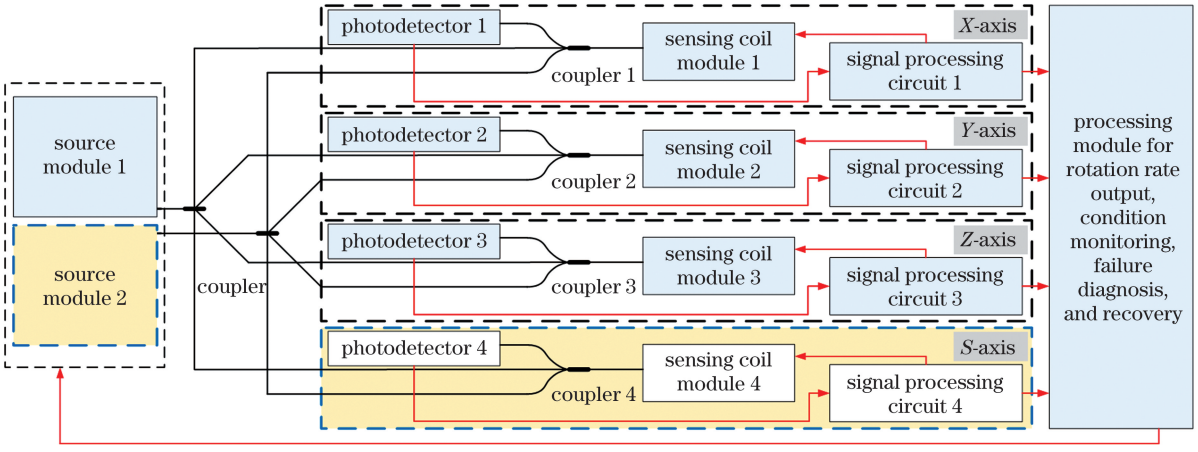

图 3 双光源四轴光纤陀螺结构示意图

Fig. 3 Configuration of four-axis IFOG with two sharing light sources

$$C_{\mathrm{rw_}e}=\frac{\lambda c}{2\pi LD}\sqrt{\frac{2e}{P}+\frac{1}{\Delta v}+\frac{2eI_{\mathrm{d}}}{P^{2}}+\frac{4kT}{RP^{2}}},\tag{2}$$

式中：k 为玻尔兹曼常量；T 表示温度；e 为电子电荷；Δv 表示光源频谱带宽；R 表示探测器跨阻；I_{d} 表示探测器暗电流；P 表示系统的光功率值。基于随机游走系数估算方法和空间辐射等因素影响，空间用光纤陀螺随机游走系数预测模型可表示为[14-15]

$$C_{\mathrm{rw_}p}=\frac{\lambda c}{2\pi LD}\sqrt{\frac{2e}{\eta P_{0}10^{-(A_{\mathrm{c}}+Lqr^{b}d^{f})/10}}+\frac{1}{\Delta v}+\frac{2eI_{\mathrm{d}}}{(\eta P_{0}10^{-(A_{\mathrm{c}}+Lqr^{b}d^{f})/10})^{2}}+\frac{4kT}{R(\eta P_{0}10^{-(A_{\mathrm{c}}+Lqr^{b}d^{f})/10})^{2}}},\tag{3}$$

式中：η 表示探测器的响应度；P_{0} 表示耦合入光路的光源功率；A_{c} 表示由光纤耦合器、集成光路和熔接部分所产生的全部光路损耗；q、b、f 为光纤辐射敏感常数；d 是辐射剂量；r 是辐射剂量率。

设 $\max(C_{\mathrm{rw_}p})$ 是正常情况下 $C_{\mathrm{rw_}p}$ 在整个空间任务中的最大值，陀螺正常工作时，满足

$$C_{\mathrm{rw_}e}\leqslant\max(C_{\mathrm{rw_}p})。\tag{4}$$

若 $C_{\mathrm{rw_}e}>\max(C_{\mathrm{rw_}p})$，则判定陀螺光路故障。

利用 Allan 方差计算在轨数据随机游走系数实时值 $C_{\mathrm{rw_a}}$，当随机游走系数在轨计算值与随机游走系数估计值的偏差大于设定的阈值 T_{h}，即 $|C_{\mathrm{rw_a}}-C_{\mathrm{rw_}e}|>T_{\mathrm{h}}$ 时，则可判定为陀螺电路故障。诊断流程如图 4 所示。

2.2 小型化技术

对于高可靠、长寿命应用需求背景，双光源四轴一体化的光纤陀螺设计方案是一种典型、高效的配置方案，但是敏感轴组件的整体冗余仍使基于该方案设计的光纤陀螺组件质量和功耗较高。近年来逐渐成为热点的低轨微纳卫星应用场景，对光纤陀螺进一步的轻质化、低功耗提出了更高要求。

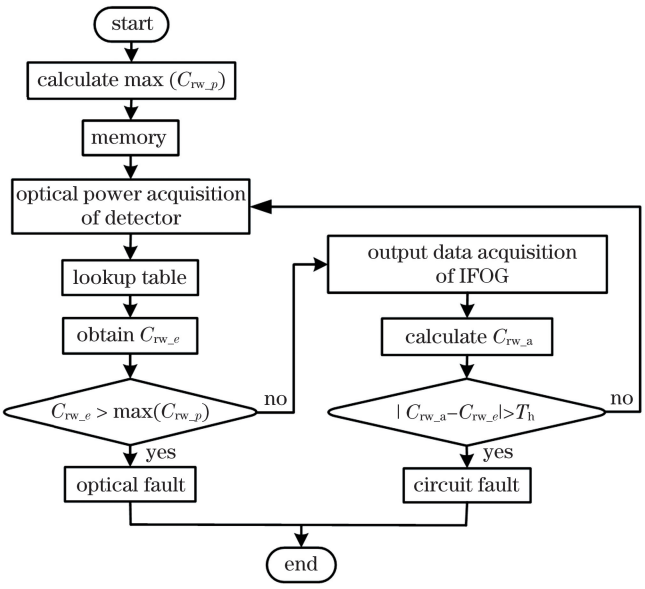

图 4 光纤陀螺故障诊断流程图

Fig. 4 Flow chart of IFOG fault diagnosis

针对上述问题，图 5(a)展示了一种轻小型三轴一体光纤陀螺配置方案，正交设置的三轴陀螺通过耦合器与光源模块相连。此外，利用时分复用技术能够进一步实现光纤陀螺的小型化，图 5(b)中基于时分复用技术的设计是目前三轴一体光纤陀螺的最简配置方案。该方案在图 5(a)的基础上，再次简化了光纤陀螺的组成结构，仅使用一个耦合器和一个光电探测器，减少了光路复杂度和光纤熔点的个数，仅使用一套信号处理电路，大大减小了陀螺组件的质量和功耗。信号处理电路采用时分复用技术，在陀螺工作过程中，三轴按照一定顺序交替工作，通过对三个轴向的 IOC 施加适当调制，使每个时刻只有一个轴向的陀螺工作在有效状态下，在现场可编程门阵列(FPGA)中对各时刻数字信号进行解调、积分、反馈等处理，从而实现三轴时分复用光纤陀螺的数字闭环。在空间应用中光源的故障率最高，上述两个配置方案可以通过增加备份光源来提高可靠性。

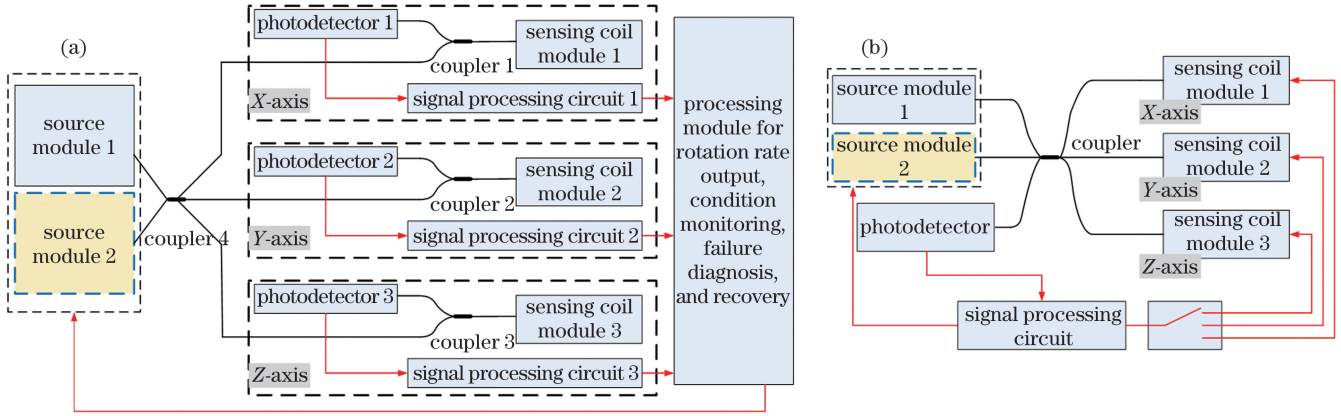

图 5 进一步小型化的三轴一体光纤陀螺。(a)轻小型三轴一体光纤陀螺；(b)时分复用三轴一体光纤陀螺

Fig. 5 Configuration of 3-axis IFOGs with further miniaturization. (a) Miniature 3-axis IFOG; (b) 3-axis IFOG based on TDM technology

时分复用技术通过对光路和电路的进一步复用，能够实现多轴一体光纤陀螺的最简结构，但也带来了很多问题，如信息量损失、各轴数据串行处理带来的动态性能劣化、轴间串扰等[16-18]。在硬件结构简化的同时，软件的复杂程度大大提高，这也增加了时分复用光纤陀螺的开发难度。对于 N 轴一体的时分复用光纤陀螺，在 N 个轴向全部闭环工作一次的周期内，陀螺输出数据的样本容量缩减为原来的 $1/N$，这使得极限精度劣化为非分时状态的 $1/\sqrt{N}$，而各轴切换过程中的过渡过程使得信息量再一次缩减，造成了时分复用光纤陀螺在动态特性上的劣势[19]。不过，综合考虑光纤陀螺体积、功耗、成本与精度、动态特性，折中设置分时参数，在中低精度的空间应用需求中，时分复用光纤陀螺仍然具有很强的竞争优势。时分复用光纤陀螺探测器检测的光信号来自各个敏感环路的信号叠加，使得探测器的散粒噪声与光源的强度噪声成为影响陀螺精度的主要因素。选择合适的调制和解调方案可以降低串扰噪声带来的信噪比劣化[20-22]。

除此以外，光电器件的小型化也是陀螺小型化的重要手段。在同样的配置方案下，应用细径光纤、小型光源、小型 IOC、集成 PIN 结-场效应晶体管(PIN-FET)光接收组件、优化的小型集成数字处理电路等能够明显减小光纤陀螺的体积和质量。图 6 展示了部分光纤陀螺小型化器件。利用涂敷层直径 100 μm 的细径保偏光纤(PMF)，绕制出的光纤环平均直径可降至 19 mm。

2.3 耐辐照技术

卫星在轨运行期间面临恶劣的空间辐射，由此造成的光纤辐射致衰减(RIA)严重影响和限制陀螺仪精度，尤其是对于在高轨道运行的卫星，辐照的影响更加突出，因此有必要进一步提升光纤陀螺的耐辐照性能。1991 年由 Russell 提出、1996 年南安普顿大学首次制成的光子晶体光纤(PCF)在抗辐射方面的优势已从理论和工程上得到了验证。保偏光子晶体光纤(PM-PCF)的辐射致衰减只有常用保偏光纤的几十分之一，采用光子晶体光纤的设计能够大幅提升陀螺的耐辐照性能[23]。然而由于传输损耗大、熔接难度高、熔点可

表 3 北京航空航天大学典型空间用光纤陀螺产品

Table 3 Typical spacial IFOGs developed by Beihang University

Model	Miniature four-axis IFOG	Miniature three-axis IFOG	PM-PCF IFOG
Appearance			
Bias stability (100 s, 1σ) /[(°)·h^{-1}]	≤0.02	0.2	≤0.002
Random walk coefficient /[(°)·h$^{-1/2}$]	≤0.005	0.05	≤0.0004
Scale factor performance /10^{-6}	≤50	≤100	≤10
Dimension /mm	135×135×100	80×80×50	–
Mass /kg	≤2	≤0.4	–
Power consumption /W	≤10	≤4	–

图 9 零偏与噪声地面测试结果。(a)小型四轴光纤陀螺;(b)小型三轴一体光纤陀螺;(c)光子晶体光纤陀螺

Fig. 9 Results of bias drift and noise test for the IFOGs. (a) Miniature four-axis IFOG; (b) miniature three-axis IFOG; (c) PM-PCF IFOG

4 结 论

本文基于空间环境的独特背景需求,首先介绍了双光源共享的四轴一体光纤陀螺方案,该方案实现了对全部光纤陀螺光学器件的双重备份,在消除了组件单点失效的同时,大大减小了组件的质量、尺寸和功耗。用于提高光纤陀螺可靠性的在轨故障诊断技术普遍适用于多轴一体光纤陀螺,全数字的实现方案不会给组件带来额外的成本。其次,小型化三轴一体的光纤陀螺配置对空间环境下易失效器件做了更有针对性的备份,避免了过度冗余造成的浪费,更加适用于微纳卫星。在此基础上,利用时分复用技术能够实现多轴光纤陀螺的最简配置,配合小型化器件,质量、体积、功耗和成本将大幅降低。最后,光子晶体光纤的低辐射损耗特性能够进一步提升光纤陀螺的耐辐照性能,这为光纤陀螺在空间环境适应性上带来更大的优势。

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Fiber Optic Gyroscopes for Space Applications

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Abstract

Significance Interferometric fiber optic gyroscopes (IFOGs) are angular velocity measurement sensors based on the Sagnac effect. With the unique advantages of high performance, high sensitivity, anti-irradiation and high reliability as a solid-state technology with no moving parts, IFOGs have become the significant devices of inertial navigation and orbit and attitude control systems on satellites and spacecrafts.

In recent years, satellite technology has developed rapidly, especially in low-orbit, miniaturized, and high-throughput satellite technology. According to the Union Concerned Scientists (UCS) satellite database, as of January 1, 2022, 4852 satellites were in orbit around the Earth, of which 511 belonged to China. The development of satellite technology has put forward new requirements for IFOGs in space. On the one hand, it is a high-reliability technology. In the satellite fault analysis, the failure rate of the orbit and attitude control subsystems is always at a high level. As the core component of the orbit and attitude control subsystems, in the design process of the IFOGs, ensuring reliability should always be put in the first place. From high-intensity vibration during launch to galactic cosmic radiation, high-energy particles, thermal vacuum, etc. after entering orbit, the complex and harsh space working environments require that IFOGs must be fully prepared in terms of resisting external disturbances and improving environmental adaptability. Especially in the high orbit, high inclination, and deep space operation environment, the energy, dose rate, and cumulative radiation dose of space particles are greatly increased. It is significant to improve the anti-irradiation performance of IFOG components. On the other hand, it is a miniaturization technology. While ensuring lifetime and performance, the device with lower power consumption, lighter weight, and lower cost is always a better choice.

Resources will be further limited when applied to small satellites especially. Therefore, research on miniaturization is necessary to enhance the competitiveness of IFOGs in low or medium precision applications.

Progress At present, the IFOG products of industrial sectors in Europe and the US have been applied in the space field in batches. The companies including iXblue in France, Northrop Grumman and Honeywell in the US, and Optolink and Fizoptika in Russia have rich experience in the development and application of spacial IFOGs. With the continuous miniaturization and environmental adaptability improvement, IFOG products are increasingly used in various small spacecrafts. In recent years, with the development of related technology, the level of domestic IFOGs has conjointly been rapidly improved, which play roles in a growing number of space missions, such as Tiangong-1, Shenzhou series spacecrafts, Chang'e series of lunar probes and several in-orbit satellites. After years of research, Beihang University starting from the two routes of high-reliability and miniaturization has successively made breakthroughs in key technologies such as structural configuration optimization, detection technology innovation, functional density improvement, and components upgrading of IFOGs for space. Several spacial IFOGs developed by Beihang University are working stably on more than 60 in-orbit satellites.

This paper reviews several key technologies of IFOGs for space applications developed by Beihang University. The dual-light-source four-axis IFOG solution is first introduced (Fig. 3), and the in-orbit fault diagnosis technology of IFOGs is described (Fig. 4). This is based on the desire for high reliability and downsizing. It has significant advantages over the conventional six-independent-axis redundancy approach in terms of weight, dimension, and power consumption while achieving double backup. The configuration of miniature three-axis IFOGs and the simplest three-axis configuration made possible by time-division multiplexing (TDM) technology are introduced in order to further realize downsizing (Fig. 5). Including source backup, the reliability can be increased. Additionally, an IFOG design based on polarization-maintaining photonic crystal fiber (PM-PCF) is demonstrated to further enhance the anti-irradiation performance. The typical IFOG products for space developed by Beihang University are presented in Table 3.

Conclusions and Prospects The IFOGs should be highly reliable due to the hostile space environment. The dual-light-source four-axis arrangement that was presented offers double backup for all of the IFOG components, considerably increasing reliability. The in-orbit fault diagnosis approach is typically applicable to multi-axis IFOGs, which enhances the IFOG's environmental adaptability while avoiding additional costs associated with all-digital implementation. In order to prevent resource waste brought on by excessive redundancy, a more focused redundant backup is designed for space applications with relatively mild operating environments based on the failure modes and failure rate of components in space. The simplest scheme of the three-axis IFOG could be achieved by the TDM technology. The mass, volume, power consumption, and cost will be significantly decreased, and the device shrinking makes it more appropriate for tiny spacecraft like small satellites. The introduction of the PCF scheme demonstrates an important development trend for IFOGs: improved anti-irradiation properties due to low radiation induced attenuation (RIA) of PCF.

Key words fiber optics; fiber optic gyroscope; space applications; in-orbit fault diagnosis; time division multiplexing; photonic crystal fiber