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题目

耐高温碳化硅光纤法珀

微振动传感器技术研究

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摘 要

高温振动测试技术是航空发动机、高超声速飞行器等国家重大工程领域开展关键部件设计优化、安全评估与性能提升的重要手段。航空发动机内部环境温度极高且振动特性复杂,振动信号呈现频域跨度大、幅值变化剧烈等特征,导致高温振动信号难以实现实时获取与高精度解调。针对航空发动机关键部件对耐高温、大量程、宽频带振动信号测量的迫切需求,本文围绕碳化硅光纤法珀微振动传感器技术,在传感器芯片结构设计、优化、关键微纳加工工艺、耐高温低应力封装以及高动态信号解调等方面开展了系统性研究。结合航空发动机典型部件环境试验,验证了传感器在高温-振动耦合复杂工况下实时测量的可行性。本文的主要研究内容与创新点如下:

(1) 系统分析了碳化硅光纤法珀振动传感器的光-力-热敏感特性,基于多光束干涉机理构建了 F-P 腔长与光谱响应解析模型,阐明了反射率对干涉条纹特性的影响规律。提出了复合 F-P 腔与 EFPI-FBG 耦合两种温度补偿结构,实现了温度解耦与腔长实时补偿。基于二阶单自由度振动系统解析模型,建立了四端固支梁与 L 型梁结构的刚度系数与阻尼特性解析式。结合结构设计准则与指标要求,通过有限元仿真确定了芯片关键结构尺寸,并通过压膜阻尼调控将传感器的平坦工作频带拓宽至 3000Hz ($\pm 10\%$)。通过热-力耦合分析,明确了底部封装形式的低应力优势,揭示了热失配对结构应力分布的影响规律,表征了传感器在 20-600°C 范围内的腔长温度漂移特性。

(2) 针对碳化硅材料难加工问题,提出了基于双光刻负胶填充与均匀性调控的厚镍掩膜电镀工艺,有效解决了掩膜横向生长导致的形貌劣化问题,实现了垂直度 88°、厚度 21.2 μm 高质量厚镍掩膜制备。构建了基于 ICP-RIE 的碳化硅干法刻蚀工艺体系,通过气体比例优化、功率与腔室温度动态调节,有效抑制了“长草”、“V 型槽”等典型刻蚀缺陷,实现了侧壁垂直度优于 $90^\circ \pm 2^\circ$ 的 315 μm 碳化硅深刻蚀,以及深宽比大于 5:1、深度 152 μm 窄槽刻蚀。完成了表面粗糙度从 $R_a > 200\text{nm}$ 黑碳化硅减反结构到 $R_a < 3\text{nm}$ 光滑结构的可控调节。通过异宽结构刻蚀动力学均衡,显著削弱了碳化硅大异宽比刻蚀中的 lag 效应,使大线宽四端固支梁与小线宽 L 型结构的刻蚀速率误差控制在 1% 以内。结合等离子体活化与高温退火工艺优化,确定了 1300°C、3MPa 的最优退火参数,将键合强度提升至 11.2MPa,完成了三层碳化硅晶圆键合与传感器芯片制备。

(3) 建立了基于高斯光束理论的光学准直与耦合模型,分析了近距与远距耦合的光路损耗机制与容差特性,明确了在 F-P 腔长 $200 \pm 20\mu\text{m}$ 、对准误差 $s < 2\mu\text{m}$ 、 $\theta < 0.5^\circ$ 条件下可实现耦合效率 $\eta_c > 90\%$ 的近距耦合封装方案。设计了基于钼锆钛合金外壳的双层密封封装结构,通过热应力匹配与应力释放槽设计有效抑制了热应力集中。结合高温准直与光路调校平台,实现了传感器的耐高温、低应力高精度准直封装。通过模态分析、半

正弦冲击仿真与高温热应力仿真评估封装体在振动、冲击及高温环境下的结构响应，验证了封装结构的环境适应性与可靠性。

(4) 针对传感器在高动态信号解调中的性能瓶颈，系统分析了强度、波长与相位三类解调方法的优缺点，明确了相位解调法在高动态、高精度应用中的优势。设计了基于多光谱仪集成的分时复用架构，通过多通道并行采样与阶梯式曝光将系统采样率由 25kHz 提升至 100kHz。结合光谱整形与窗函数带通滤波技术，实现了背景光源及低频噪声抑制，有效增强了 F-P 腔频率分量的信号质量。提出融合希尔伯特变换与 CORDIC 旋转的 HT-CORDIC 高速解调算法，通过 FPGA 实现快速相位差求解，在满帧率条件下仅需 8 次迭代 (80ns) 即可将腔长解调误差收敛至 2.9nm。引入高次谐波互相关算法，通过增强主峰对比度解决了干涉级次判错导致的温漂补偿精度不足问题。

最后，通过常温与高温振动试验平台对研制的耐高温碳化硅光纤法珀微振动传感器进行了标定，获得了灵敏度 3.02nm/g、频率响应 20-3000Hz ($\pm 10\%$)、幅值线性度 0.38%、重复性误差 0.55%、回程误差 0.99% 以及 600°C 温度漂移率 3.54% 等核心性能指标。基于标定结果开展了某型航空发动机典型部件验证试验，实现了超过 30 分钟全周期高温振动连续测量。通过快速傅里叶变换与小波分析提取了试验件不同工作阶段的主频与振动幅值，并捕获了满负载工况下的多模态频率响应。结果表明，该传感器能够在高温、强振动及强耦合复杂环境下实现稳定、可靠的实时振动测量。研究成果为极端高温环境下振动信号原位测量与高精度提取提供了创新性技术方案，为航空发动机健康监测、燃烧控制与寿命评估等应用奠定了重要技术基础。

关键词：碳化硅；法布里-珀罗；高温振动；微纳制造；光纤传感

Abstract

High-temperature vibration testing is a critical technique for design optimization, safety assessment, and performance enhancement of key components in major national engineering applications such as aero-engines and hypersonic vehicles. The internal environment of aero-engines features extremely high temperatures and complex vibration characteristics. The vibration signals exhibit a wide frequency span and drastic amplitude variations, making real-time acquisition and high-precision demodulation of high-temperature vibration signals particularly challenging. In response to the urgent demand for high-temperature-capable, large-dynamic-range, and wide-bandwidth vibration measurement in aero-engine key components, this dissertation conducts a systematic study on silicon-carbide-based fiber-optic Fabry-Perot (F-P) micro vibration sensor technology, covering sensor chip structural design and optimization, key micro-nano fabrication processes, high-temperature low-stress packaging, and high-dynamic-range signal demodulation. Environmental tests representative of typical aero-engine components were performed to verify the feasibility of real-time sensing under combined high-temperature and high-vibration conditions. The major research contents and contributions are summarized as follows:

(1) The optical-mechanical-thermal sensitivities of SiC fiber-optic F-P vibration sensors were systematically analyzed. An analytical model correlating F-P cavity length with spectral response was derived based on the multi-beam interference mechanism, revealing the influence of reflectivity on fringe characteristics. Two thermal compensation structures composite F-P cavities and EFPI-FBG coupled cavities were proposed to achieve temperature decoupling and real-time cavity-length compensation. Based on a second-order single-degree-of-freedom vibration model, analytical expressions for the stiffness coefficients and damping characteristics of four-side clamped beams and L-shaped beams were established. Guided by structural design criteria and performance requirements, the key geometric parameters of the sensor chip were determined through finite-element simulations. Pressure-film damping control was employed to extend the flat operational bandwidth to 3000Hz ($\pm 10\%$). Thermo-mechanical coupling analysis further elucidated the low-stress advantages of bottom-side packaging, revealed the effect of thermal mismatch on structural stress distribution, and quantified cavity-length temperature drift within 20-600°C.

(2) To address the difficulty of machining SiC, a thick-nickel masking process based on dual-photolithography negative-resist filling and uniformity control was developed. This

approach effectively mitigated lateral growth-induced mask degradation, enabling high-quality nickel masks with a verticality of 88° and a thickness of $21.2\mu\text{m}$. A SiC dry-etching framework based on ICP-RIE was established. Through optimization of gas ratios, RF power, and chamber temperature, typical SiC etching defects such as “grass” formation and “V-groove” bottom morphology were effectively suppressed. High-precision deep etching of SiC was achieved, including $315\mu\text{m}$ etch depth with $90^\circ\pm 2^\circ$ sidewall verticality, aspect ratios above 5:1, and $152\mu\text{m}$ deep narrow trenches. Surface roughness was controllably tuned from $R_a>200\text{nm}$ (black SiC anti-reflection texture) to $R_a<3\text{ nm}$ (smooth surface). By balancing etching kinetics across structures with disparate widths, the lag effect in SiC etching was significantly reduced, limiting the etch-rate mismatch between wide four-side-clamped beams and narrow L-beam structures to within 1%. Using plasma activation and high-temperature annealing optimization, the optimal bonding conditions were determined as 1300°C and 3MPa , achieving a bonding strength of 11.2MPa . Based on these results, three-layer SiC wafer bonding and sensor chip fabrication were successfully completed.

(3) An optical collimation and coupling model based on Gaussian-beam theory was established, analyzing optical-path loss mechanisms and tolerance characteristics under both near-field and far-field coupling regimes. A near-field coupling packaging scheme achieving coupling efficiency $\eta_c>90\%$ was designed under cavity length $200\pm 20\mu\text{m}$ and alignment tolerances $s<2\mu\text{m}$ and $\theta<0.5^\circ$. A dual-layer hermetic package employing a molybdenum-zirconium-titanium alloy shell was developed, where thermal-stress matching and stress-relief slot design effectively suppressed stress concentration. A high-temperature alignment and optical-path calibration platform was constructed to achieve high-precision, low-stress collimation packaging. Modal analysis, half-sine shock simulation, and high-temperature thermo-stress simulations were conducted to evaluate the mechanical and thermal reliability of the packaged device, demonstrating strong environmental adaptability.

(4) To overcome the performance bottlenecks in high-dynamic-range signal demodulation, intensity-, wavelength-, and phase-based demodulation methods were compared in detail, clarifying the advantages of phase demodulation for high-dynamic and high-precision applications. A time-division-multiplexed architecture integrating multiple spectrometers was developed, where multi-channel parallel sampling and stepwise exposure increased the system sampling rate from 25kHz to 100kHz . Spectral shaping and window-based band-pass filtering were implemented to suppress background illumination and low-frequency noise, thereby enhancing the quality of the F-P cavity frequency component. A high-speed HT-CORDIC demodulation algorithm combining Hilbert transformation and CORDIC rotation was proposed

and implemented on FPGA hardware. Under full-frame operation, cavity-length demodulation errors converged to 2.9nm within only eight iterations (80ns). A high-order harmonic cross-correlation method was further introduced to enhance main-peak contrast, resolving fringe-order identification errors that previously limited temperature-drift compensation accuracy.

Finally, the developed high-temperature SiC fiber-optic F-P micro vibration sensor was calibrated using both room-temperature and high-temperature vibration platforms. The sensor demonstrated a sensitivity of 3.02nm/g, a 20-3000Hz ($\pm 10\%$) frequency response, 0.38% amplitude linearity, 0.55% repeatability error, 0.99% hysteresis error, and a 600°C temperature drift of 3.54%. A validation experiment on a typical aero-engine component achieved continuous high-temperature vibration measurement for over 30 minutes across a full operation cycle. FFT and wavelet analyses were used to extract dominant frequencies and vibration amplitudes at different operational stages, successfully capturing multimodal frequency responses under full-load conditions. The results confirm that the proposed sensor enables stable and reliable real-time vibration measurement in harsh environments characterized by high temperatures, strong vibrations, and strong multiphysics coupling. The research outcomes provide an innovative technical solution for in-situ high-temperature vibration measurement and high-precision signal extraction, and establish a solid technical foundation for aero-engine health monitoring, combustion control, and life-prediction applications.

Key words: Silicon carbide; Fabry-Perot; High-temperature vibration; Micro/Nano manufacturing; Fiber-optic sensing