國立臺灣大學工學院機械工程學研究所

碩士論文

Department of Mechanical Engineering

College of Engineering

National Taiwan University

Master Thesis

基於波長調制微型化雷射干涉之長行程精密位移量測系統研發

Development of a Miniaturized Wavelength-modulation-based Laser Interferometric system for Long-range Precision Displacement Measurement

廖承鈺

Chen-Yu Liao

指導教授：陳亮嘉 博士

Advisor: Liang-Chia Chen, Ph.D.

中華民國 112 年 8 月

August 2023

doi:10.6342/NTU202303066

中文摘要

光纖式感測器因其抗電磁干擾、體積小以及能在惡劣環境中應用之特性，被廣泛的應用在各類型之感測器上，因應產業對微型精密位移感測器之需求，光纖式位移量測干涉儀一直是一項熱門的研究主題。本研究研發了一種微型化之光纖菲佐式雷射干涉儀系統，其探頭大小為 Φ11 mm × 27 mm，與目前市面上商用之位移量測干涉探頭之體積小了 10 倍以上，光源使用了 1550 nm 波長的 DFB 二極體雷射，並使用載波相移法 (phase generated carrier) 對雷射的波長進行 300 kHz 的弦波調制，干涉架構運用光纖端面之反射光做為參考光，簡化了干涉系統的光學架構。本研究中提出了一套創新式的動態電流波長調制法，結合了掃頻干涉術使干涉訊號之調制深度能被鎖定，克服了原先波長調制法中調制深度會隨著光程差改變的問題，使量測距離大幅的提升。此外發展了一套用於 1550 nm 波段的鎖頻方法，使用氰化氫（HCN）氣體的吸收譜線來對雷射進行鎖頻，透過動態調整雷射之工作溫度來穩定雷射之波長及確保測量的可追溯性。並以量測環境參數的方法實作了對空氣折射率補正的功能。為了評估本研究提出之干涉儀性能，我們做了一系列之實驗,實驗結果顯示本干涉儀靜態時的標準差在 1 分鐘內可達到 0.7 nm、在 300 mm 的量測範圍內，位移量測結果與 Keysight (HP) 商用干涉儀之量測差值皆小於 40 nm、且能成功的量測出壓電平台之 10 nm 步進運動，以及驗證了雷射鎖頻和空氣折射率補正之功能。本研究成果（智慧財產權申請中）將可為半導體精密製程產業提供精確的定位回饋，是精密工程領域的一項具體技術創新和突破。

關鍵詞：位移量測干涉儀、動態電流波長調制法、掃頻干涉術、氰化氫、雷射鎖頻

doi:10.6342/NTU202303066

Abstract

Fiber optic sensors have gained significant attention due to their small size, low cost, immunity to electromagnetic interference, and ability to measure in hostile environments. Among these sensors, the fiber displacement measuring interferometer is a popular research topic cause of industry demand for small and precise displacement measurement sensors. In this study, we present the development of a new compact fiber laser interferometer with the size of Φ11 mm × 27 mm, which is 10 times smaller than the commercial interferometer probe. And a 1550 nm wavelength DFB laser is utilized as the system's light source. In the proposed system, the reflection from the end face of the optical fiber as the reference beam simplifies the system's configuration. And a phase generated carrier (PGC) method is utilized by modulating the wavelength to a frequency of 300 kHz. And we developed a novel method called dynamic current wavelength modulation, which compensates the modulation depth by precisely predicting the optical path difference (OPD) by frequency sweeping interferometry to achieve consistent modulation depth over an extensive measurement range. Additionally, a wavelength-locking method was developed for the 1550 nm band, using the absorption peak of hydrogen cyanide (HCN) gas to monitor the central wavelength of the laser. This method dynamically adjusts the laser's operating temperature to stabilize the wavelength of the laser source and ensure the traceability of the measurement. And the refractive index is corrected by measuring the environmental parameters method. The experimental results showed that when the system is static, the standard deviation of the interferometer could reach 0.7 nm within one minute. The differences are less than 40 nm compared to the Keysight (HP) commercial interferometer within the 300 mm measurement range. Also, the 10 nm step movement of the piezo stage could be successfully measured. Lastly, the functions of wavelength-locking and refractive index compensation are validated. The outcome of the research can offer precise positioning feedback for the semiconductor precision manufacturing industry, representing a tangible technical innovation and breakthrough in the field of precision engineering.

Keywords: displacement measuring interferometers, dynamic current wavelength modulation, frequency sweeping interferometry, hydrogen cyanide, wavelength-locking

doi:10.6342/NTU202303066