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

In this study, we present the development of a new compact fiber laser interferometer with the size of 2.6 cm^3, which is 10 times smaller than the commercial interferometer probe. 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 lock the central wavelength of the laser. 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. We have verified this difference is from the environmental control. If the environment is controlled, this difference can be further reduced. 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.

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Displacement Measurement Interferometers (DMIs) are vital in various applications necessitating exact positioning capabilities, such as steppers or scanners in semiconductor processing, ultra-precision machining devices, atomic force microscopes, scanning electron microscopes, and nanoscale three-dimensional coordinate measuring machines. Conventional commercial interferometers, large in sensor size and demanding specific optics for measurement (R. Kneppers & A. Amstelveen, 1999) are less suited for micron object measurement or integration into machinery for inline process positioning control. Hence, numerous studies have suggested using fiber optics for light and interference signal transmission, facilitating the miniaturization of the interferometer system (F. Shabahang & S. T. Smith, 2022). Fiber optics allows design flexibility in the interferometer and offers the benefit of electromagnetic interference resistance.

Since DMIs employ the wavelength of laser light as a reference for measurement, the light source's wavelength is a crucial factor in DMIs. Numerous studies have addressed laser frequency stabilization, incorporating methods such as using iodine gas absorption lines for helium-neon lasers (J. Ishikawa, 2009) and the Zeeman stabilization technique (L. L. Deck, 2002). These methods commonly stabilize the laser wavelength by dynamically adjusting the length of the laser cavity, unavoidably leading to a more substantial and complicated sensor structure.

The modulation and demodulation techniques of the interference signal greatly influence the performance of displacement measurement interferometers. The most prevalent demodulation technique is the Phase-Generated Carrier (PGC) method (A. Dandridge et al., 1982). This method amplifies the interference signal's sensitivity and ensures uniform sensitivity across various phases while mitigating errors caused by light source intensity drift. Multiple strategies exist for modulating the optical phase, including the use of piezoelectric materials to alter the optical path difference (Z. Yu et al., 2019), the application of an electro-optic modulator (EOM) to generate distinct delays in the optical phase (L. Yan et al., 2018) and the modulation of the laser diode's injection current to generate changes in the laser wavelength (Q. Shi et al., 2010). Among these techniques, current- wavelength modulation offers high-speed modulation, eliminates the need for additional optical components, and is independent of the polarization state. However, it also has a downside: the modulation depth may fluctuate with the optical path difference, which restricts the measurement range.

In this study, we present a compact Fizeau fiber-based DMI module. We propose and implement a novel method called the dynamic current-wavelength phase-generated carrier (PGC) technique, which enhances the accuracy and stability of measurements while significantly extending the measurement range. Furthermore, we introduce a laser wavelength stabilization method rooted in hydrogen cyanide (HCN) gas absorption within the 1550 nm wavelength range.

研究方法

一、動態電流波長載波法 (Dynamic Current-wavelength PGC Method)

In the proposed method, the injection current of the laser diode is controlled to achieve wavelength modulation. The intensity of the modulated interference can be described as

$$I = A + I_{mod}\cos(\omega_{mod}t) + B\left[\cos 2kL - \frac{4\pi L\delta\lambda}{\lambda_0^2+\delta\lambda\lambda_0\cos(\omega_{mod}t)}\cos(\omega_{mod}t)\right] \quad (1)$$

where A represents the DC term of the signal. Because the injection current is modulated, which in turn results in the modulation of the light's intensity, so I_{mod} stands for the modulation of the intensity; ω_{mod} is the modulation frequency; t is the time; B corresponds to the amplitude of the interference signal; L is the distance between the reference mirror and target mirror as shown in **Figure 1**; c signifies the speed of the light; λ_0 denotes the laser's center frequency; $\delta\lambda$ is the wavelength modulated amplitude; $k = 2\pi/\lambda_0$ is the wave number.

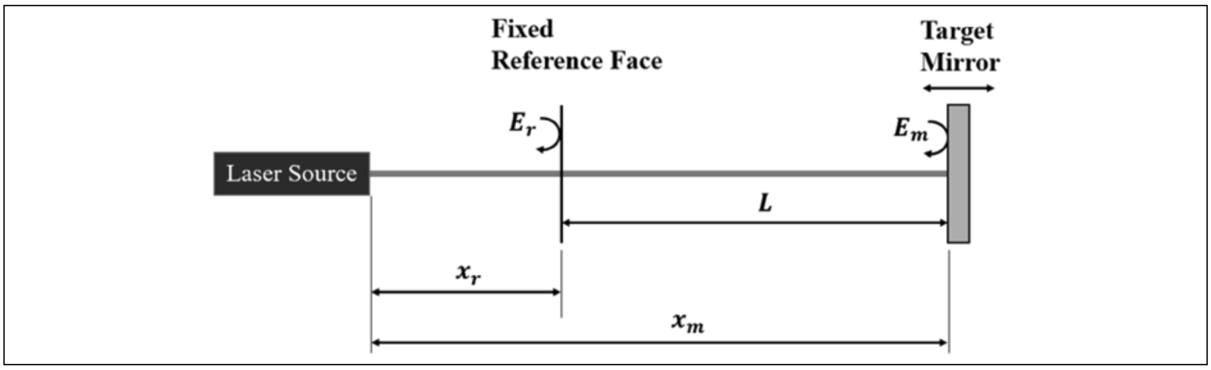

Figure 1. Schematic of the developed Fizeau interferometer

The modulated interference can be expanded by the Jacobi–Anger expansion

$$
\begin{aligned}
I=A+&[I_{mod}-2B\sin(2kL)\,J_1(C)]\cos(\omega_{mod}t)\\
&+B\left\{\cos(2kL)\left[J_0(C)+2\sum_{n=1}^{\infty}(-1)^n J_{2n}(C)\cos(2n\omega_{mod}t)\right]\right.\\
&\left.+\sin(2kL)\left[2\sum_{n=2}^{\infty}(-1)^n J_{2n-1}(C)\cos((2n-1)\omega_{mod}t)\right]\right\}
\end{aligned}
\tag{2}
$$

where J_i represents the Bessel function of the first kind and C is the modulation depth of the interference signal

$$C=\frac{4\pi L\delta\lambda}{\lambda_0^2+\delta\lambda\lambda_0\cos(\omega_{mod}t)}\approx\frac{4\pi L\delta\lambda}{\lambda_0^2} \tag{3}$$

we can ignore the term $\delta\lambda\lambda_0\cos(\omega_{mod}t)$ because the wavelength modulation amplitude is usually at the picometer level. And the term $\delta\lambda\lambda_0\cos(\omega_{mod}t)$ is five orders smaller than the term λ_0^2.

Equation (3) shows that a quadrature signal carrying displacement information, represented by $cos(2KL)$ and $\sin(2KL)$, can be modulated onto the odd and even harmonics of the modulation frequency. This equation also shows that the intensity modulation is incorporated into the first harmonic. Many PGC methods employ the modulated frequency's first and second harmonics as mixers, as outlined in references (A. Dandridge et al., 1982). However, in the dynamic current-wavelength PGC method, using the first and second harmonics to extract the quadrature signal may introduce an error due to the intensity modulation. **Figure 2** presents a simulation of the interference signal and the demodulated phase when the target mirror moves at a constant speed. The results reveal that the demodulated phase suffers from periodic errors, and the center of the Lissajous circle is not situated at the origin. We use the third and second harmonics to circumvent this error to extract the quadrature signal.

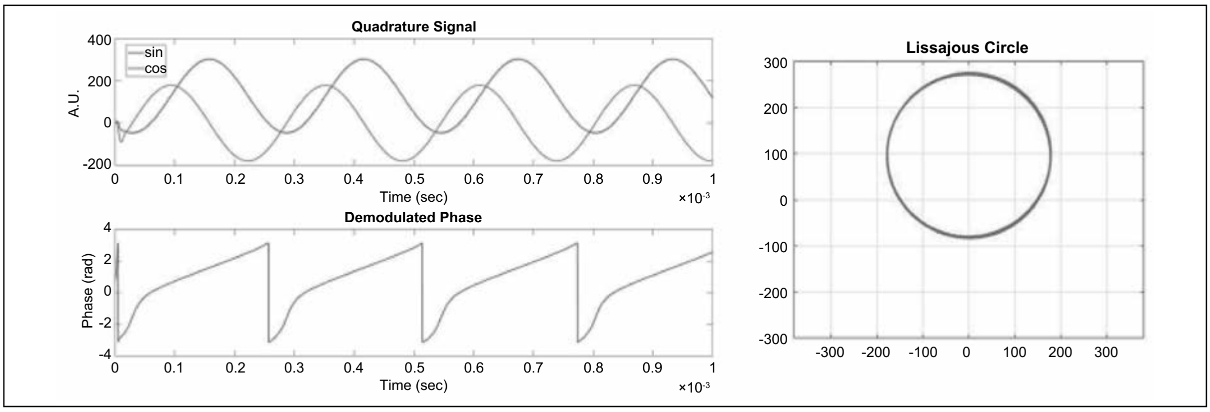

Figure 2. Simulation result of using first and second harmonic as the mixers

The modulated interference signal first undergoes a mixing process in the demodulation process. This mixed signal is then subject to low-pass filtering, which extracts the quadrature signal. The interference phase is obtained by calculating the arctangent of the quadrature signal as

$$\text{Arctan}\left(\frac{J_3(C)\sin(2kL)}{J_2(C)\cos(2kL)}\right)=2kL \tag{4}$$

when $C=3.77$

then the result can be converted into a displacement value if the modulation depth is 3.77. **Figure 2** visually illustrates the process of demodulation. However, the computed interference phase is only accurate if the amplitudes of the quadrature signals are identical. In this scenario, the amplitude of the quadrature signal depends on the modulation depth, denoted as C. Specifically, when C equals 3.77, the amplitude of the quadrature signal matches. On the other hand, **Eq. (3)** indicates that in the traditional current-wavelength PGC method, the modulation depth is influenced by the distance, L. This connection restricts the measurement range of the method. If the distance undergoes substantial changes, one of the quadrature signals may dwindle to zero, leading to a failure in phase computation.

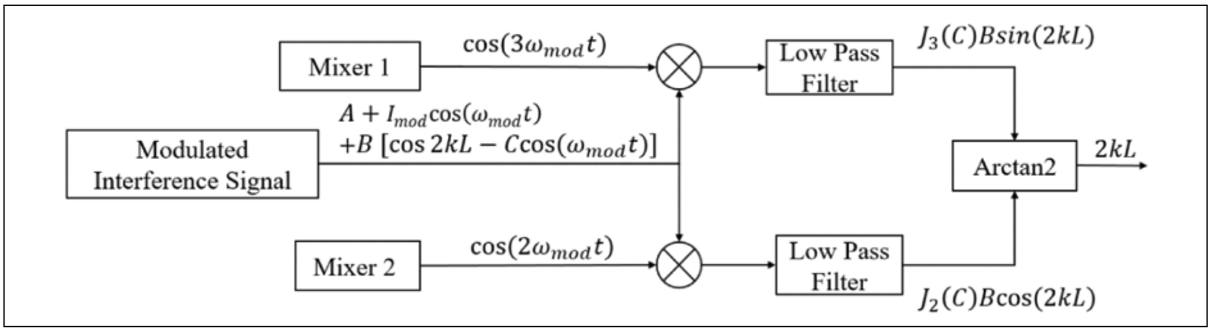

Figure 3. Dynamic current-wavelength PGC demodulation process

Thus, it is crucial to ascertain the value of distance L to maintain a fixed modulation depth. We suggest the adoption of frequency scanning interferometry (FSI) (S. Kakuma & Y. Katase, 2012) for the measurement of distance L , and denoted as L_{FSI} , enabling the wavelength- modulated amplitude to function as a distance variable when the modulation depth is set at 3.77 and can be described as

$$\delta\lambda=\frac{3.77\lambda_0^2}{4\pi L_{FSI}} \tag{5}$$

It's important to note, however, that while the accuracy of these measurements may not match those of the incremental interferometer, they can be sufficient to determine the amplitude of optical frequency modulation.

In traditional interferometry, the wavelength is typically constant while the distance to the target mirror (L) varies. Contrastingly, in frequency scanning interferometry (FSI), the optical frequency undergoes a linear scan

$$v(t)=v_0+\frac{\delta v}{T}t \tag{6}$$

where v_0 represent the starting optical frequency; δv denotes the scanning depth; T signifies the sweeping period; and t is the time. Suppose the distance to the target mirror (L) remains stable during scanning. In that case, the phase shift of the interference signal denoted as $\Delta\phi$ becomes proportional to the distance (L). By measuring this phase shift of the interference signal, the distance can be inferred as

$$L_{FSI}=\frac{c}{4\pi\delta v}\Delta\varnothing \tag{7}$$

And the **Figure 4** presents the algorithm associated with the dynamic current-wavelength PGC method. When the system is initialized or the interferometer is zeroed, Frequency Scanning Interferometry (FSI) is initially utilized to assess the distance L between the target mirror and the reference mirror. Subsequently, **Eq. (5)** is employed to compute the wavelength-modulated amplitude. The measured displacement can then be tracked by integrating it with the initially calculated distance, and the amplitude of the wavelength modulation can be controlled to uphold the modulation depth at 3.77 consistently.

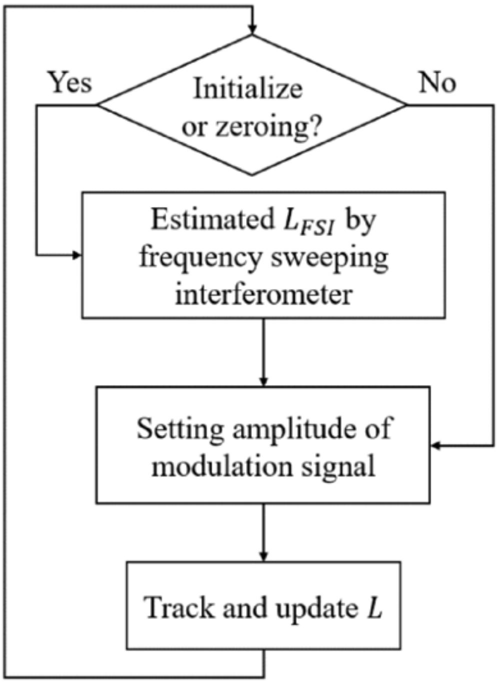

Figure 4. Algorithm of dynamic current-wavelength PGC method

二、HCN 氣體雷射鎖頻法

The Displacement Measuring Interferometer (DMI) uses the laser's wavelength as a measurement standard, so the wavelength must remain stable and traceable. To this end, our study suggests using an HCN gas cell for laser stabilization. The HCN gas exhibits multiple absorption spectra within the 1550 nm wavelength range. According to the data provided by NIST (S. L. Gilbert, W. C. Swann, and C.-M. Wang, 2005) the wavelength uncertainty attainable with HCN gas can be as precise as 0.2 picometers.

In our study, a sinusoidal signal is used to modulate the laser wavelength. Consequently, the Pound-Drever-Hall (PDH) frequency-locking technique can be integrated into our application (E. D. Black, 2001). This technique blends the transmitted light signal from the gas cell with a signal that maintains the same frequency and phase as the modulation signal. After low-pass filtering, an error signal is produced, representing the wavelength deviation.

Figure 5 (left) illustrates different modulation points on the HCN absorption peak. When the laser's center wavelength is situated at position 1, the modulation and gas cell signals are out of phase, resulting in a negative error signal. Conversely, both signals are in phase when the center wavelength is at position 2, yielding a positive error signal. A zero error signal implies that the central wavelength is at position 3, locked to the absorption line. **Figure 5 (right)** demonstrates the simulation results depicting the relationship between wavelength deviation and the corresponding wavelength error signal

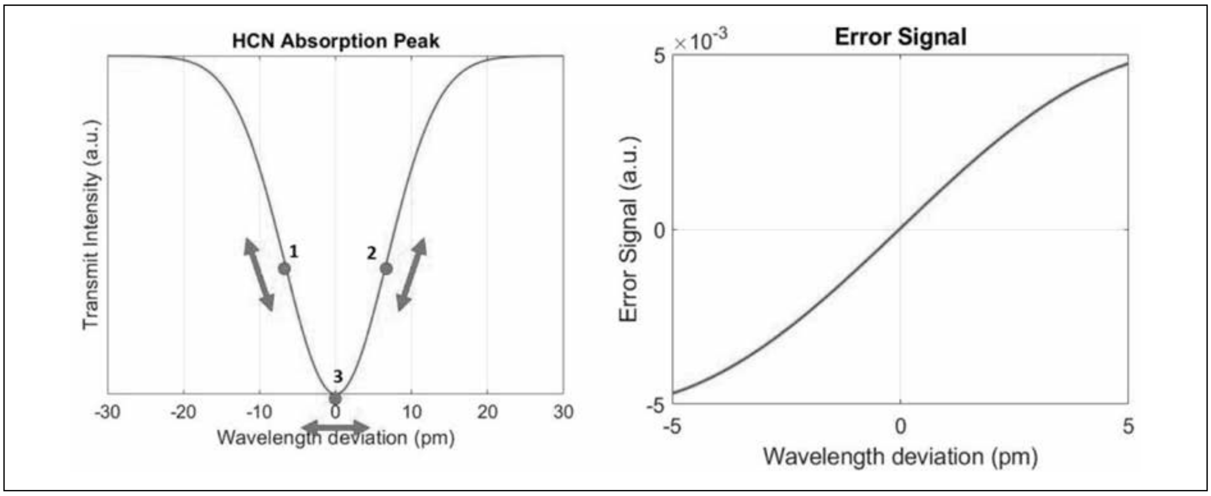

Figure 5. P7 absorption peak of HCN and the wavelength error signal

Given that the wavelength of the diode laser can be modulated by altering the operating temperature, a laser temperature controller, working in tandem with the wavelength error signal and a proportional-integral (PI) controller, can stabilize the wavelength. If the wavelength drifts, the temperature controller modifies the laser's operating temperature based on the error signal. **Figure 6** provides a schematic representation of the proposed method for wavelength stabilization.

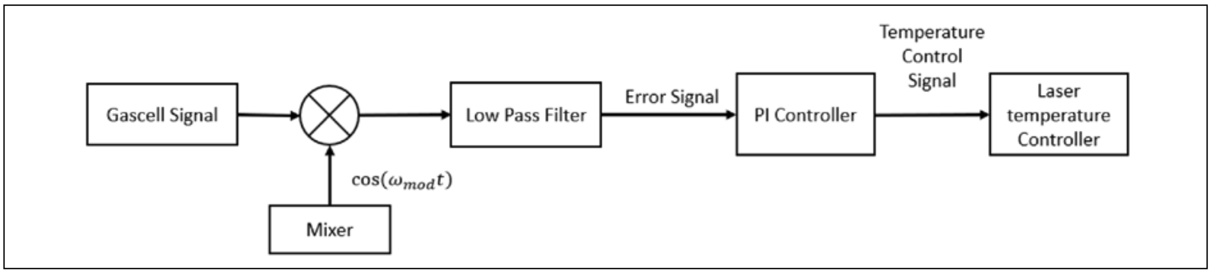

Figure 6. Schematic of proposed wavelength stabilization method

實驗架構

Figure 7 illustrates the experimental setup, which can be segmented into several modules: the interferometer module, the interferometer probe module, and the signal and control module. The signal and control module comprises the National Instrument (NI) signal input/output (I/O) chassis, a laser temperature, and a current controller.

The operational principle of the experimental system is as follows: The interferometer probe module captures the interference signal and conveys it to the interferometer module via optical fibers. The interferometer module, in turn, transmutes the optical interference signal into an electrical one and relays it to the NI chassis. The signal can then be read via an industrial personal computer (IPC), and demodulation algorithms can be implemented to convert the interference signal into displacement data.

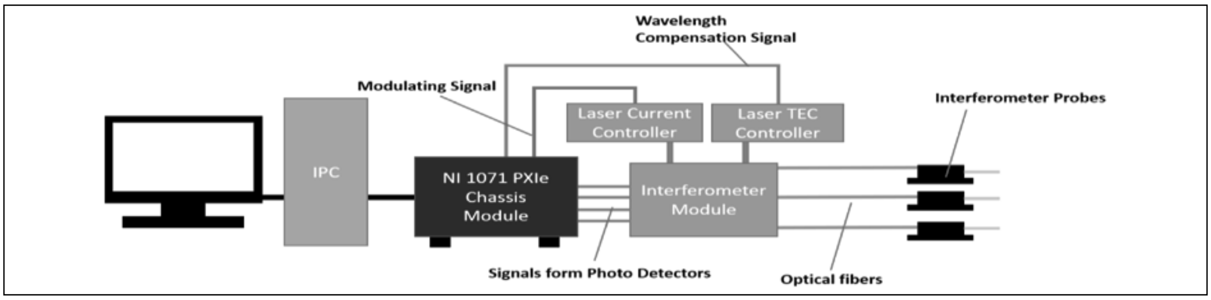

Figure 7. Configuration of the system

一、干涉儀探頭模組

This study aims to minimize the influence caused by environmental disturbances. We utilize a Fizeau interferometer configuration that maximizes the common optical path. **Figure 8** shows the proposed fiber Fizeau interferometer probe the size of the probe is only 2.6 cm3. The reference beam reflects from the end face of the FC/PC fiber connector, and the collimator intentionally uses an FC/APC connector, which has an 8-degree angle. The design prevents multi-beam interference and eliminates the need for additional external beam splitters. Furthermore, this design maintains a common optical path until the FC/PC fiber connector's end face, making the system less susceptible to environmental disturbances.

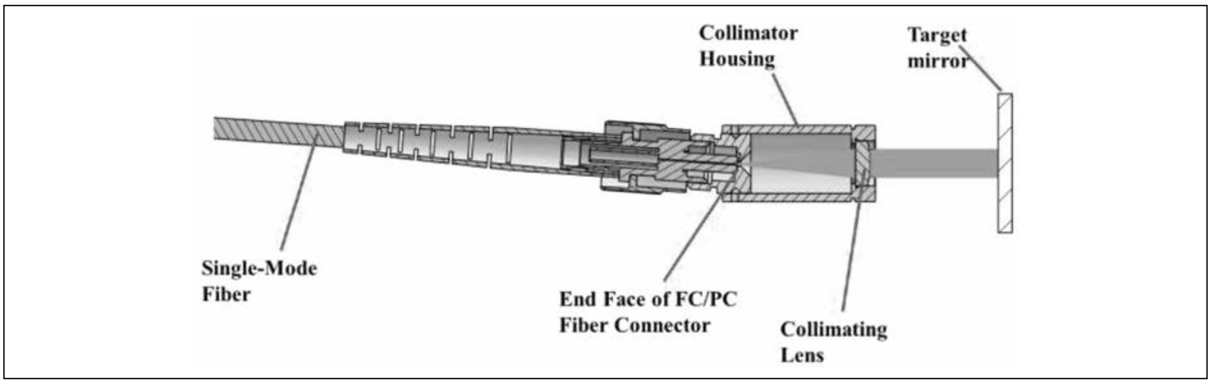

Figure 8. Proposed fiber-coupled Fizeau interferometer probe

二、干涉儀模組

Figure 9 presents the schematic of the interferometer module. A 1550 nm fiber-coupled DFB laser diode serves as the light source. The emitted light is divided into two paths by a 90:10 fiber splitter. The bulk of the light (90%) is guided through an attenuator for intensity modulation. Post-attenuation, the light is split by a 1x4 fiber splitter. Three output paths from this splitter are linked to port 1 of individual fiber circulators. Light entering port 1 is redirected to port 2, which is connected to the fiber connector of the interferometer probe. The interference signal detected by the probe is reflected in port 2 and subsequently guided to port 3 by the fiber circulator. Port 3 is connected to the photodetector (PD), responsible for converting the optical interference signal into an electrical one. This electrical signal is then relayed to the input/output module of the NI system.

The remaining light (10%), split by the initial fiber splitter, traverses through an HCN gas cell. Light that passes through the gas is directly linked to PD4. It is worth noting that all the fiber components in the diagram utilize FC/APC connectors for their fiber connectors to minimize noise induced by reflected light.

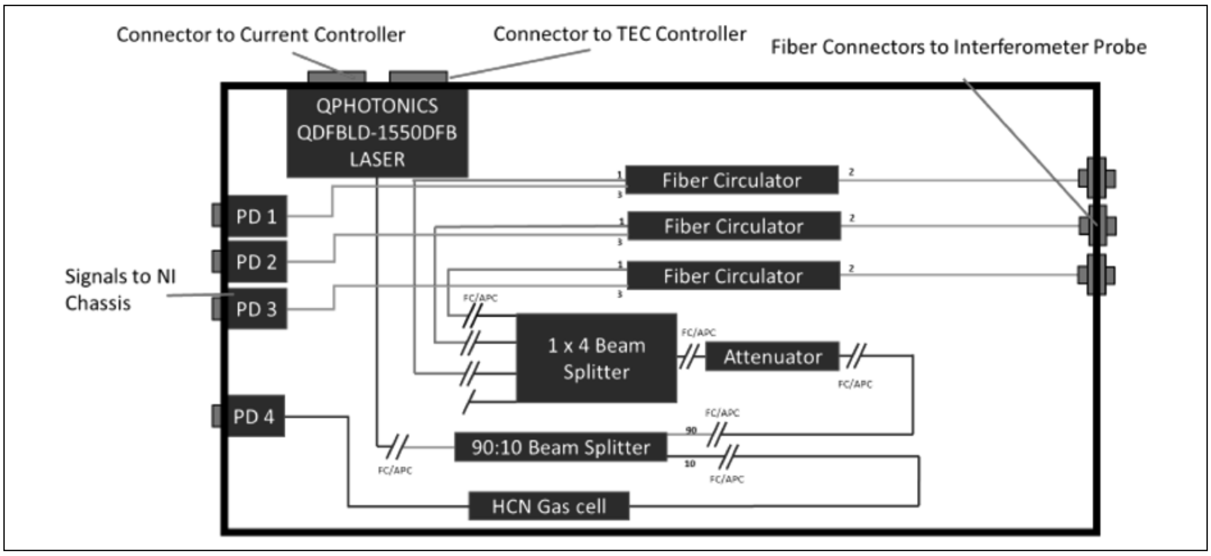

Figure 9. Schematic of interferometer module

For the demodulated quadrature signals to have identical amplitudes, the modulation depth must be fixed at 3.77. As such, the system needs to dynamically adjust the amplitude of the wavelength modulation contingent on the reference mirror's position. It should be noted that the central wavelength of the laser is locked at 1547.435 nm, corresponding to the P7 absorption peak of the HCN gas cell.

實驗結果

一、系統穩定度測試

A stability test was conducted by positioning the interferometer probe near a fixed target mirror. Given the concise optical path length difference between the reference mirror and the target mirror, any wavelength or air refractive index variations would have minimal impact on the measured values. Hence, if the acquired data demonstrate considerable drift, it signifies the system's instability. As shown in **Table 1**, the proposed system's standard deviation over a 1- minute is 0.7 nm, while the standard deviation over a 10-minute interval is 3.4 nm.

Table 1. Stability testing results

Period	Standard deviation (nm)
1 Minute	0.7
10 Minutes	3.4

Furthermore, the data collected over 10 minutes can discern a drift phenomenon. This situation is likely attributable to changes in temperature, which lead to the expansion or contraction of the fixed mechanism, culminating in alterations in the distance between the reference mirror and the target mirror. These results underscore that the proposed interferometer can measure displacements at nanometer scales or even smaller, provided that environmental factors and wavelength variations are effectively managed.

二、長行程位移量測實驗

To verify the effectiveness of the displacement measurement module developed in this research, the interferometer probe was installed on a wafer measurement machine constructed at the Precision Metrology Lab at National Taiwan University. The experimental setup is depicted in **Figure 10**. The actuating system employs the Aerotech ABL80040 air-bearing stage, capable of a travel range of 300 mm in both X and Y axes.

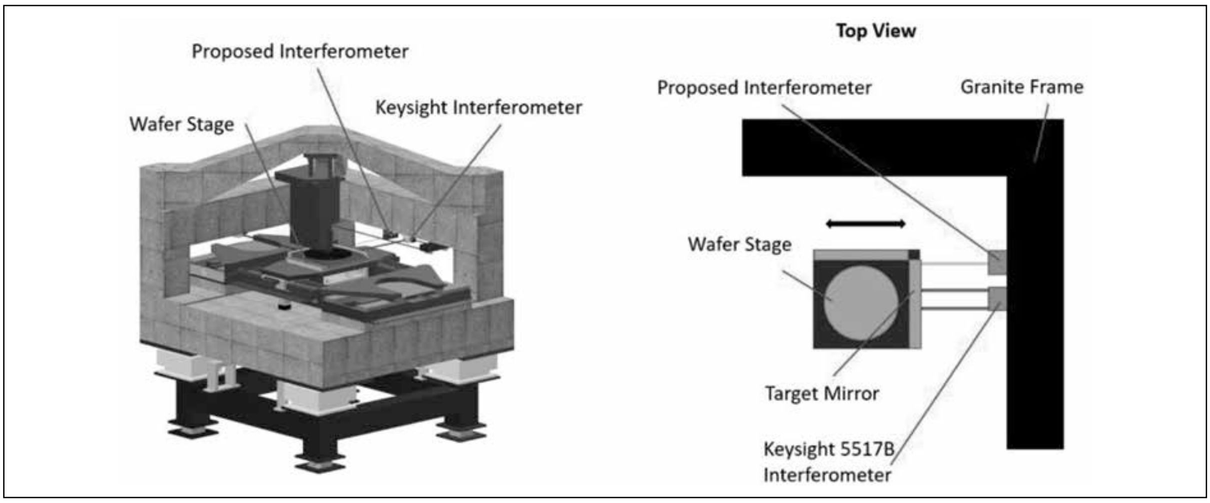

Figure 10. Long-range displacement measuring setup

In this experiment, the wafer machine moves at 10, 50, 100, 200, and 300 mm displacements, each distance being repeated 90 times. The interferometer probe proposed in this study and the calibrated Keysight 5517B interferometer was installed beneath the machine's granite beam to measure the displacements simultaneously. The experimental results are outlined in **Table 2**. The discrepancy between the proposed interferometer and the commercial interferometer within a 300 mm displacement is within ±40 nm. This situation suggests a high degree of agreement between the proposed module and the calibrated Keysight system when measuring long-range displacements. Additionally, the standard deviation of the differences is within 35 nm, indicating minimal variations in the measured differences for identical displacements, thus showcasing the system's precision.

Table 2. Result of long-range displacement measuring experiment

Displacement (mm)	STD of proposed Interferometer module (nm)	STD of Keysight 5517B interferometer (nm)	Average deviation (nm)	STD of Deviation (nm)
10	11.9	13.1	-20.6	15.9
50	15.9	15.4	6.2	17.6
100	22.6	21.1	39.9	22.6
200	25.9	22.3	-35.5	20.4
300	44.3	28.0	10.0	34.4

Furthermore, it's notable that even when the measured displacement reaches 300 mm, the system can still maintain a deviation within tens of nanometers. This result highlights the effective mitigation of the limitations associated with the current carrier wavelength method in measuring long-range travel, as proposed in this study.

結論

This research presents a fiber-optic Fizeau interferometer for displacement measurement, overcoming multiple-beam reflection issues using angled fiber connectors. The novel dynamic current-wavelength PGC method is introduced for carrier modulation, maintaining the consistent amplitude of demodulated quadrature signals across various distances and outperforming previous wavelength-carrying techniques. Laser frequency stabilization is achieved via an HCN gas absorption method and dynamic temperature adjustment. The developed interferometer showed impressive static stability of 0.7 nm within a minute and consistency with a calibrated laser interferometer, with bias errors within 40 nm over 300 mm. These findings open new avenues for improvements and applications in precision measurement, beneficial for inline semiconductor manufacturing processes.

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