Nanometric Displacement Measurement System Using Three-Longitudinal-Mode He-Ne Laser

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Abstract

In this paper, design and simulation of a nanometric displacement measurement system is discussed. The combination of the Doppler effect and interferometry method is being used. A stabilized three-longitudinal-mode He-Ne laser with $6328 A^o$ wavelength and $35cm$ cavity length is used. Its primary and secondary beat frequencies are 428.60MHz, 429.27MHz, and 670kHz, respectively. Therefore, the maximum measurable velocity is equal to $106 mm/s$ .Also, the measuring displacement is limited to the fraction of the synthetic wavelength and its accuracy will be decreased to 0.09nm.

Keywords: He-Ne laser, three-longitudinal-mode, stabilized laser, Doppler-interferometry.

1-Introduction

The fabrication improvement of microelectronic devices in photolithography and masking process is impossible without measurements of the accurate displacement in different axes [1]. There are different methods for nanometric displacement measurement, but the effective one is the interferometry method. Principles of classical multiple wavelength interferometry (MWI) method has been designed for the first time in 1895. Then, it has been improved by designing of advanced laser cavity [2]. For this purpose a multimode laser or combination of several lasers with different wavelengths was used.

If we consider the two-wavelength interferometry using the optical wavelength λ_1 and λ_2, then the phase shift for each wavelength will be,

$$\Delta\Phi_i = \frac{2\pi}{\lambda_i}.2d \qquad (1)$$

where d is the optical path difference and Φ_i is the phase shift corresponding to the wavelength λ_i . Therefore, the phase difference between Φ_1 and Φ_2 is given by

$$\Delta\Phi = 2\pi\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right).2d \qquad (2)$$

And the synthetic wavelength can be expressed as

$$\Lambda = \lambda_s = \frac{\lambda_1\lambda_2}{|\lambda_1 - \lambda_2|} = \frac{C}{|\nu_1 - \nu_2|} \qquad (3)$$

where ν_1 and ν_2 are the optical frequencies corresponding to λ_1 and λ_2, and C is the velocity of light in vacuum.

The He-Ne laser can be applied to MWI, using different laser lines, for example at $0.62934\mu m$ and $0.6328\mu m$. This allows us to obtain synthetic wavelength about $117\mu m$ [3]. Therefore, with combination of λ_1 and λ_2, and reaching to synthetic wavelength, Λ , the maximal measurable displacement will increase. This value (d_{max}) , considering maximum phase shift of π , is equal to $\lambda_1 / 4$.

2- Doppler Interferometry using Three-Longitudinal-Mode Laser

If the length of He-Ne laser cavity is increased, as a result, the space between modes, $\frac{C}{2L}$, decreases. Because of this effect, the number of modes will increase at the Doppler broadened gain curve. However, the curve for the neon in a He-Ne laser will have a half-width in the order of $1.5GHz$. So, for a $35cm$ length cavity there are three stabilized longitudinal modes.

By utilizing the stabilized 3-mode He-Ne laser; there will be three inter-mode beat frequencies, against the two-mode type, which has only one inter-mode beat frequency. On the other hand, at three-mode laser, the secondary beat frequency, ν_b , is much smaller than the other beat frequencies (ν_1, ν_2).

Figure 1 depicts the optical head of the designed nanometric displacement measurement system using the stabilized three-longitudinal-mode He-Ne laser. The stabilized cavity is too necessary for having the high accuracy in the displacement measurement systems [5-7].

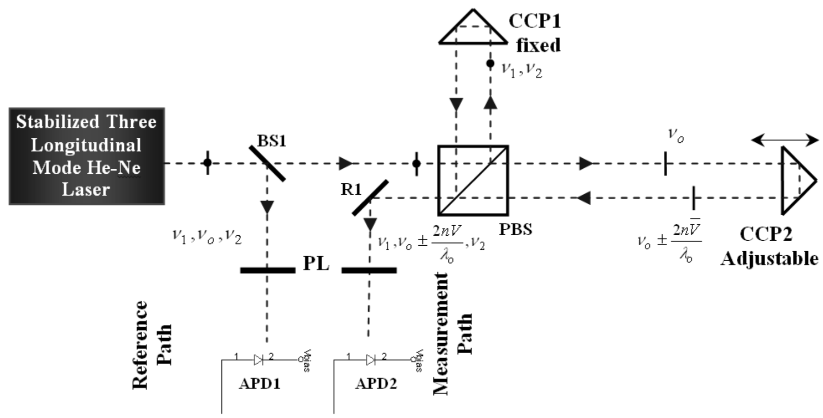

Fig.1: The optical head of the nanometric displacement measurement system using three-longitudinal-mode He-Ne laser.

As is shown in figure 1, the beam with frequency ν_o is passed through polarizing beam splitter (PBS) and the beam having frequencies ν_1 and ν_2, are reflected. The reference signal is expressed as,

$$I_{APD_1} = \left[\begin{array}{r} E_1\cos(2\pi\nu_1 t) + E_2\cos(2\pi\nu_2 t) + \\ + E_o\cos(2\pi\nu_o t) \end{array}\right]^2 \quad (4)$$

The high frequency terms will be eliminated by the reference avalanche photodiode, APD_1, and the Eq.4 can be rewritten as

$$\begin{aligned} I_{APD_1} &= A\cos(2\pi(\nu_2-\nu_1)t) + \\ &+ B\cos(2\pi(\nu_2-\nu_o)t) + C\cos(2\pi(\nu_o-\nu_1)t) + D \\ I_{APD_1} &= A\cos(2\pi(\nu_H+\nu_L)t) + B\cos(2\pi\nu_H t) + \\ &+ C\cos(2\pi\nu_L t) + D \end{aligned} \quad (5)$$

where $\nu_H+\nu_L >> \nu_H, \nu_L$, $A = E_1E_2$, $B = E_oE_2$, $C = E_oE_1$ and $D = 0.5(E_1^2+E_2^2+E_o^2)$. Similarly, the output current of the APD_2 is

$$I_{APD_2} = \left[\begin{array}{r} E_1\cos(2\pi\nu_1 t) + E_2\cos(2\pi\nu_2 t) + \\ + E_o\cos\left(2\pi\left(\nu_o \pm \frac{2nV}{\lambda_o}\right)t + \Phi\right) \end{array}\right]^2 \quad (6)$$

$$\begin{aligned} I_{APD_2} &= A'\cos(2\pi(\nu_H \mp \Delta\nu)t - \Phi) + \\ &+ B'\cos(2\pi(\nu_L \pm \Delta\nu)t + \Phi) + \\ &+ C'\cos(2\pi(\nu_H+\nu_L)t) + D' \end{aligned} \quad (7)$$

The represented signals in Eq.5 and Eq.7 will be squared by analog mixer such as double balanced mixer (DBM). Table 1 presents the reference and measurement signals.

According to table 1, $\nu_b = \nu_H - \nu_L$ and $\nu_b \pm 2\Delta\nu$ signals with the phase shift of -2Φ can be filtered from reference and measurement frequencies, respectively. By measuring frequency $\nu_b \pm 2\Delta\nu$, the target velocity will be obtained. The displacement of target is obtained by the integration of velocity or by measuring the phase -2Φ, $\left(\Phi = \frac{4\pi}{\lambda}d\right)$.

If the difference of the initial and final phases between the reference and measurement signals are denoted as Φ_1 and Φ_2, respectively, and Doppler shift frequency is denoted by N, the displacement is described by [8],

$$\Delta d = \frac{\lambda}{2}\left[N + \frac{\Phi_2 - \Phi_1}{2\pi}\right] \quad (8)$$

4- The Displacement Measurement System Design

Figure 2 shows the schematic of the designed system. According to this figure, photocurrent of the avalanche photodiodes is amplified and converted to voltage signal by pre-amplifier and post-amplifier. $V_R(t)$ and $V_M(t)$ are self-multiplied with the two double balanced mixers (DBM_1, DBM_2) ,and frequency components of Table 1 are obtained. The high frequency components is eliminated by two low pass filters (LPF_1, LPF_2).

The output signal of the low pass filters (LPFs) for reference and measurement paths are described as

$$V_{o_R} = k_1\cos(2\pi\nu_b t + \varphi) \quad (9)$$

$$V_{o_M} = k_2\cos\left(2\pi\left(\nu_b \pm \frac{4n\bar{V}}{\lambda_o}\right)t - 2\Phi + \varphi\right) \quad (10)$$

The sinusoidal signals in Eqs.9-10 are converted into square wave and the secondary beat frequency, ν_b, is measured by a high bandwidth frequency up/down counter. Therefore, the number N in Eq.8 is obtained. In addition, the phase detector measures the initial and final phase between the reference and measurement signals, so the fractional part of Eq.8 will be determined. The operation of the phase detector especially in lower target velocity is important.

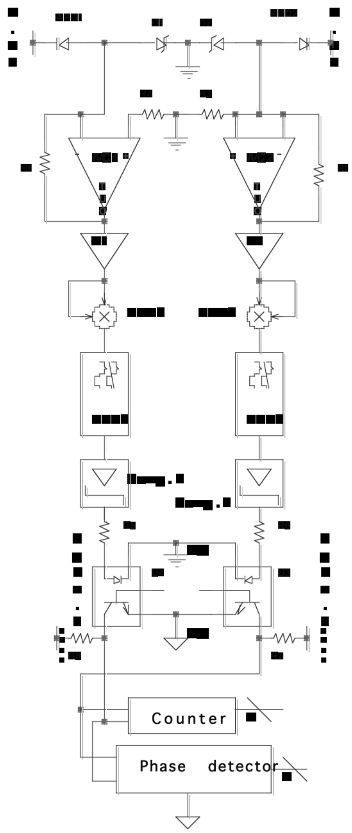

Fig.2: The schematic of the nanometric displacement measurement system using three-longitudinal-mode He-Ne laser.

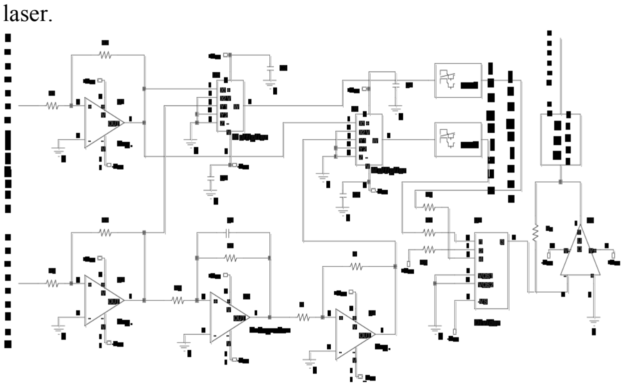

Fig.3: The phase detector section

The designed circuit for phase detector is shown in figure 3. According to this figure, the output signal of LPF_1 is amplified; and the reference signal is integrated by U_3. Then, the measurement signal is mixed at one time with reference signal as well as its integrated. The output signal of the low pass filters are $P = \sin(2\Phi)$ and $Q = \cos(2\Phi)$. The phase of $\Phi = 0.5 \tan^{-1}(P/Q)$ is produced for the processor circuit by using one divider and an analog to digital converter.

Table.1: The phase and frequency of reference and measurement signals.

Reference Signal	Measurement Signal
$2\nu_H \angle \varphi$	$(2\nu_H \mp \Delta\nu) \angle [\varphi - \Phi]$
$2\nu_L \angle \varphi$	$2(\nu_H \pm \Delta\nu) \angle [\varphi + \Phi]$
$2(\nu_L + \nu_H) \angle \varphi$	$2(\nu_L + \nu_H) \angle [\varphi]$
$\nu_H \angle \varphi$	$(\nu_L + \nu_H) \angle [\varphi]$
$\nu_L \angle \varphi$	$(\nu_L + 2\nu_H \mp 2\Delta\nu) \angle [\varphi - \Phi]$
$(\nu_L + \nu_H) \angle \varphi$	$(\nu_H \mp \Delta\nu) \angle [\varphi - \Phi]$
$(\nu_L + 2\nu_H) \angle \varphi$	$(\nu_L \mp \Delta\nu) \angle [\varphi + \Phi]$
$(2\nu_L + \nu_H) \angle \varphi$	$(2\nu_L + \nu_H \pm \Delta\nu) \angle [\varphi + \Phi]$
$(\nu_H - \nu_L) \angle \varphi$	$(\nu_H - \nu_L \mp 2\Delta\nu) \angle [\varphi - 2\Phi]$

5- Experimental and Simulation Results

To achieve a three-longitudinal-mode He-Ne laser, the use of the theoretical and experimental data at visibility curve is being considered. By considering the effect of the background, the visibility of the fringes can be defined as

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min} - 2I_{bg}} \qquad (11)$$

The visibility data can be obtained by changing the moving mirror at a step rate of $5cm$. The theoretical visibility for a laser having 3-modes is given by

$$V = \left| \sin\left(\frac{3\pi\Delta l}{L}\right) / 3\sin\left(\frac{\pi\Delta l}{L}\right) \right| \qquad (12)$$

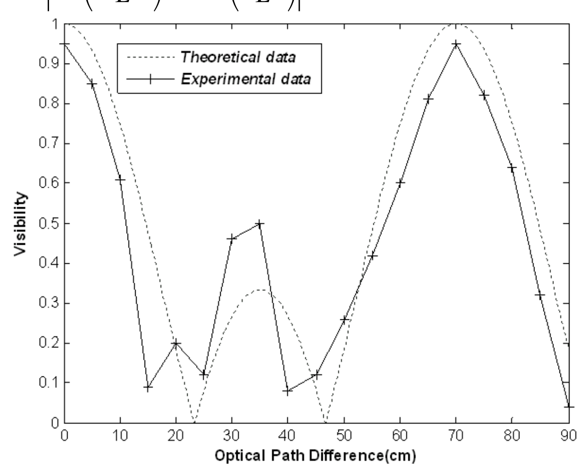

Fig.4: The theoretical and experimental results of stabilized He-Ne laser.

The theoretical and experimental data have enough conformity according to figure 4. A stabilized 3-mode He-Ne laser having 5×10^{-11} stability is used as the light source of the present system. The laser has a fundamental mode (TEM_{oo}) and its cavity length is equal to $35cm$. The longitudinal mode spacing is about $428.6MHz$, and the secondary beat frequency, ν_b, is equal to $670KHz$.

The output signals of double-balanced mixers and low pass filters for velocity of $0.0m/s$, $100mm/s$ and $50mm/s$ is shown in figure 5. Hence, in the presented system, the maximum measurable velocity is limited to

$$\left.\begin{array}{l}\Delta\nu = \dfrac{2n\overline{V}}{\lambda_o} \\ 2\Delta\nu_{\max} = \nu_b\end{array}\right\} \Rightarrow \quad \overline{V}_{\max} = \left.\frac{\nu_b.\lambda_o}{4n}\right|_{n=1} = 106mm/s \qquad (13)$$

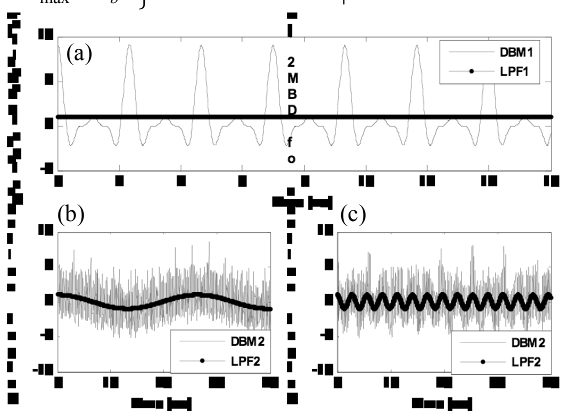

Fig.5: The output signal of DBMs. (a) target is fixed, and the target velocity equal to (b) 100mm/s and (c) 50mm/s.

Having the phase resolution equal to 0.1 degree, the displacement resolution is obtained to be 0.09nm. Certainly, at high velocity which Doppler frequency is high, it is not necessary to measure the initial and final phases. Figure 6 shows the phase shift versus linear displacement for three-longitudinal-mode and two-longitudinal-mode lasers. The nanometric displacement measurement system using two (typical) and three longitudinal modes is compared in table 2. According to this table and figure 6, the resolution of the displacement measurement in the three-longitudinal-mode is considerably increased.

Table 2: Comparing of the two systems.

Parameter	Two-mode	Three-mode
Cavity length	25cm	35cm
Wavelength	632.8nm	6328nm
Synthetic wavelength	0.5m	473.6m
Beat frequencies	600MHz	428.60,429.27, 0.67MHz
Maximum measurable velocity	21m/s	0.1m/s
Nanometric displacement resolution	0.16nm	0.09nm

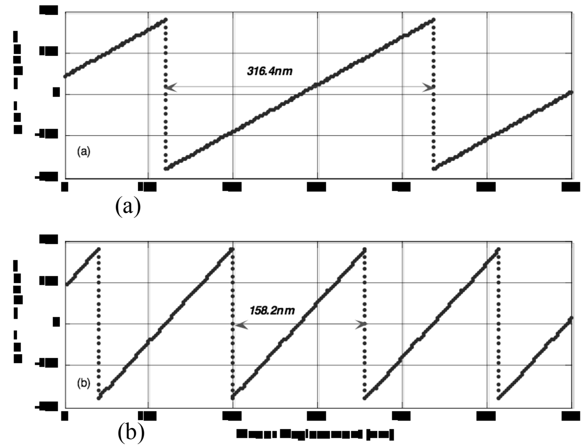

Fig.6: The shift phase in terms of the linear displacement. (a) Two-longitudinal-mode. (b) Three-longitudinal-mode.

6. References

[1] F.C.Demarest, “High resolution, high speed, low data age uncertainty, heterodyne displacement measuring interferometer electronics”, *Meas. Sci. Technol.* 9, 1024-1030, 1998.

[2] R. Dändliker, Y. Salvadé and E. Zimmermann, “Distance measurement by multiple-wavelength interferometry”, *J. Opt.* 29 (3), 105-114, 1998.

[3] R. Dändliker, K. Hug, J. Politch and E. Zimmermann, “High-accuracy distance measurements by multiple-wavelength interferometry”, *Opt. Eng.* 3 4 (8), 2407-2412, 1995.

[4] X. Yan, Z. Shu-Lian, L. Yan and Z. Jun, “Tuning Characteristics of Frequency Difference for Zeeman-Birefringence He-Ne Dual Frequency Laser”, *Chinese Phys. Lett.* 20 No 2, 230-233, 2003.

[5] T.L.Huang, Y.S.Chen, J.T.Shy AND H.P.Liu, “Two-Mode Frequency Stabilization of an Internal-Mirror 612 nm He-Ne Laser”*, Proc. Natl. Sci. Counc. ROC(A),*Vol. 24, No. 4, pp. 274-278, 2000.

[6] S.Yokoyama, T.Araki and N.Suzuki, “Intermode beat stabilized laser with frequency pulling”, *Appl. Opt.* 33, 358-363, 1994.

[7] J. Y. Yeom and T. H. Yoon, “Three-longitudinal-mode He–Ne laser frequency stabilized at 633 nm by thermal phase locking of the secondary beat frequency”, Appl. *Opt.,* 44, 266-270, 2005.

[8] N.B. Yim, C. Eom and S.W. Kim, “Dual mode phase measurement for optical heterodyne interferometry”, *Meas. Sci. Technol.* 11, 1131–1137, 2000.