

# Double sinusoidal phase modulating laser diode interferometer for thickness measurements of transparent plates

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Received March 15, 2004

A double sinusoidal phase modulating (SPM) laser diode interferometer for thickness measurements of a transparent plate is presented. A carrier signal is given to the interference signal by using a piezoelectric transducer, and the SPM interferometry is applied to measure the thickness of a transparent plate. By combining the double-modulation technique with the Bessel function ratio method, the measurement error originating from light intensity fluctuations caused by the modulation current can be decreased greatly. The thicknesses of a glass parallel plate and a quartz glass are measured in real time, and the corresponding experimental results are also given.

OCIS codes: 120.3180, 350.2460.

High-precision non-contact measurements of the thickness of transparent plates are required in many areas in science and engineering. Various kinds of interferometric methods have been proposed to measure the thickness<sup>[1-4]</sup>. Recently, the sinusoidal phase modulating (SPM) interferometry has been implemented to measure the absolute distance and displacement of an object<sup>[5-9]</sup>. In this paper, we propose a novel method for measuring the thickness of a transparent plate with frequency modulated and optical path modulated interferometer. The construction of the interferometer is very simple compared with other interferometers. A signal processing system composed of simple circuits is employed to demodulate the interference signal. The thickness signal buried in the first- and zero-order terms of the Bessel function is derived with the Bessel function ratio method.

Figure 1 shows the setup of a double SPM interferometer for thickness measurements of a transparent plate.

The injection current of a single-mode laser diode (LD) is modulated by an external sinusoidal modulation signal  $i(t) = a \cos(\omega_m t + \theta)$ . The modulation of the injection current results in both wavelength and intensity modulations, given by

$$\lambda(t) = \lambda_0 + \Delta\lambda(t) = \lambda_0 + \beta_1 a \cos(\omega_m t + \theta), \quad (1)$$

$$g(t) = g_0 + \Delta g(t) = g_0 + \beta_2 a \cos(\omega_m t + \theta), \quad (2)$$

where  $\lambda_0$  is the central wavelength of the LD,  $\beta_1$  is the modulation coefficient of the wavelength,  $\beta_2$  is a constant of proportional relationship between the output intensity and the injection current. The light passing through

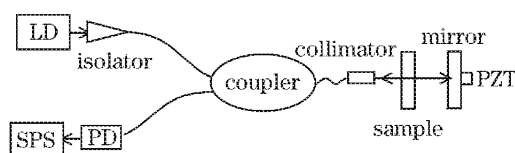


Fig. 1. Setup of the proposed interferometer for thickness measurements of a transparent plate. PZT: piezoelectric transducer; SPS: signal processing system; PD: photodiode.

an isolator is coupled into the measurement arm with a 3-dB coupler. The reference beam is reflected from the end face of the collimator, and the object beam is reflected by a mirror that is driven with a piezoelectric transducer (PZT). The vibration of the mirror is a sinusoidal motion  $L_p \sin \omega_p t$  modulated by a signal  $V_p(t) = b \sin \omega_p t$ , so the optical path difference (OPD) between the reference and object beams is  $L = \Delta L + L_p \sin \omega_p t$ , where  $\Delta L$  is the absolute distance. These two beams are detected by a photodiode (PD) as an interference signal. The ac component of the interference signal is

$$S(t) = S_1(t) \cos[z_m \cos(\omega_m t) + z_p \cos(\omega_p t + \theta) + \delta], \quad (3)$$

where

$$z_m = (2\pi a \beta_1 / \lambda_0^2) L, \quad z_p = (4\pi / \lambda) \Delta L, \quad \delta = (2\pi / \lambda_0) L, \quad (4)$$

and  $S_1(t)$  is the amplitude of the ac component.

Expanding Eq. (3), we can get

$$S(t) = S_1(t) \{ \cos \phi [J_0(z) - 2J_2(z) \cos 2\omega_m t + \dots] - \sin \phi [2J_1(z) \cos \omega_m t - 2J_3(z) \cos 3\omega_m t + \dots] \}, \quad (5)$$

where  $J_n(z_m)$  is the  $n$ th-order Bessel function. The modulation depth  $z_m$  is proportional to the OPD  $L$ . Its magnitude will change when the transparent plate is inserted into the optical setup, as shown in Fig. 1, so we can extract the difference of  $z_m$  from the interference signal to measure the thickness of transparent plate. However, the injection modulation current affects not only the wavelength of LD but also the bias intensity of the interference signal, the thickness signals buried in the Bessel functions cannot be measured accurately. To avoid this problem, the Bessel function ratio method is used to eliminate the error signal caused by the fluctuation of the light intensity, and  $z_p \cos(\omega_p t + \theta)$  is used as a carrier signal.

A SPS shown in Fig. 2 is used to demodulate the interference signal in real time.

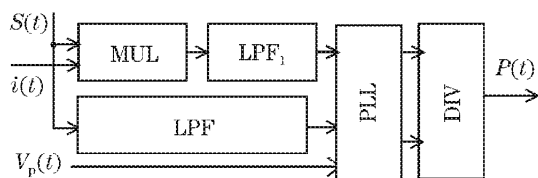


Fig. 2. Schematic diagram of the SPS. MUL: multiplier; LPF: low-pass filter; PLL: phase-locked loop; DIV: divider.

The interference signal  $S(t)$  and the modulation current  $i(t)$  are firstly fed to the discrimination circuit (DIC) composed of a multiplier and a low-pass filter (LPF<sub>1</sub>), the cutoff frequency of which is lower than one tenth of the modulation frequency. The output signal  $P_1(t)$  is given by

$$P_1(t) = K_s S_1(t) J_1(z_m) \sin\{[z_p \cos(\omega_p t + \theta) + \delta]\}, \quad (6)$$

where  $K_s$  is the transform gain of the DIC.

At the same time, the envelop term  $P_2(t)$  is obtained through signal processing of the interference signal with another LPF as the same as LPF<sub>1</sub>,

$$P_2(t) = K_1 S_1(t) J_0(z_m) \cos\{[z_p \cos(\omega_p t + \theta) + \delta]\}, \quad (7)$$

where  $K_1$  is the transform gain of LPF.  $P_1(t)$  and  $P_2(t)$  can be considered to be the sinusoidal signals with angular frequency  $\omega_p$  and amplitudes  $K_s S_1(t) J_1(z_m)$  and  $K_1 S_1(t) J_0(z_m)$ , respectively. For  $L_p \ll \Delta L$ , the term  $\Delta L + L_p \sin \omega_p t$  approximately equals  $\Delta L$ . These amplitudes can be derived by use of a phase-locked loop (PLL). We get two envelop terms associated with the Bessel functions  $P_{1dc} = K_s S_1(t) J_1(z)$  and  $P_{2dc} = K_1 S_1(t) J_0(z)$ . Then these two terms are fed into a divider, the Bessel function ratio is expressed as

$$P(t) = \frac{P_{1dc}}{P_{2dc}} = \frac{K_s S_1(t) J_1(z_0)}{K_1 S_1(t) J_0(z_0)} = \frac{K_s J_1(z_0)}{K_1 J_0(z_0)}. \quad (8)$$

Equation (8) clearly indicates that the output signal is independent on the fluctuation of the light intensity. The output signal obtained from Eq. (8) is shown in Fig. 3.

The light source used in the interferometer shown in Fig. 1 is a multi-quantum-well LD with automatic temperature controller (ATC). Its central wavelength is 1305 nm and the maximum output power is about 3 mW. The modulation coefficient of the wavelength  $\beta_1$  is 0.03 nm/mA. The collimator was a particular 0.25-pitch graded-index lens that has a diameter of 1.8 mm and a numerical aperture of 0.46. Its reflective index is 25%, much larger than that of the transparent plate, so the multiple-beam interference can be avoided in the double SPM interferometer. Because the experiments were operated on an optical bench, the noise caused by the environment was efficiently eliminated.

In the experiments, a PZT was mounted on the back of the mirror and vibrated with a frequency of 100 Hz. The frequency of the sinusoidal modulation current injected into LD was 10 kHz. The samples we measured were a parallel K9 glass plate with the thickness of

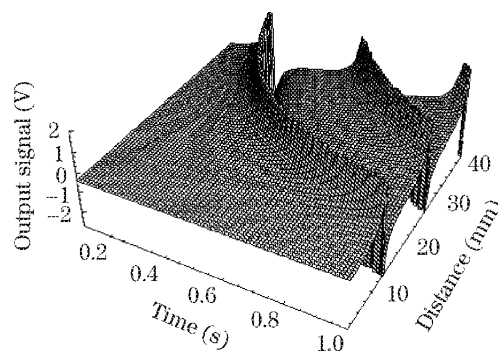


Fig. 3. Output signal versus different amplitudes of modulation current and distances.

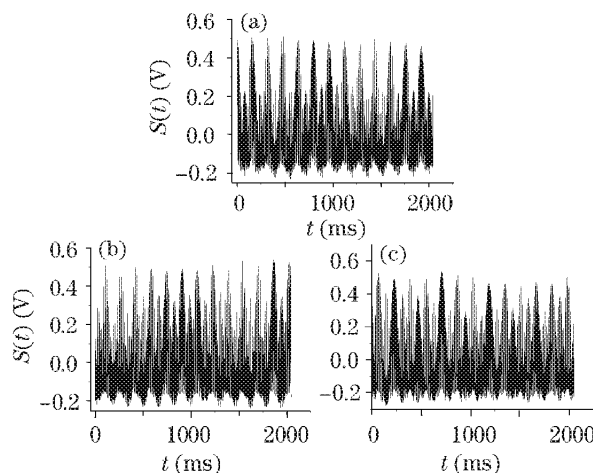


Fig. 4. Interference signals detected when the samples were not laid (a), the K9 glass plate (b) and the quartz glass (c) were laid.

2180.0  $\mu\text{m}$  and a quartz glass of 3140.5  $\mu\text{m}$ . Before setting the samples, we measured the initial OPD of the interferometer. We moved vibrating mirror along the optical axis and located it at the position where the OPD was about 10 mm, so the voltage of the output signal  $P(t)$  of SPS was not too small. Next, we placed the transparent plate between the collimator and the mirror. We measured the OPD to get the difference of  $z_m$ , and then the thickness of the sample was obtained. The detected interference signals when the samples were laid or not are shown in Fig. 4.

We measured the parallel K9 glass plate and the quartz glass several times, and the experimental standard deviations were 1.2 and 1.4  $\mu\text{m}$ , respectively.

In conclusion, by combining the phase demodulation technique with the Bessel function ratio method, we can demodulate the interference signal under both frequency modulation of the LD and the OPD modulation of PZT, and obtain a thickness of the transparent plate in real time with high-precision.

This work was supported by the National High Technology Development 863 Program of China (No. 2002AA404050) and the Foundation for Development of Science of Shanghai (No. 0214nm091). D. Li's e-mail address is ldl@siom.ac.cn.

## References

1. G. Coppola, P. Ferraro, M. Iodice, and S. De Nicola, *Appl. Opt.* **42**, 3882 (2003).
2. D. F. Murphy and D. A. Flavin, *Appl. Opt.* **39**, 4607 (2000).
3. K. Hibino, B. F. Oreb, P. S. Fairman, and J. Burke, *Appl. Opt.* **43**, 1241 (2004).
4. M. Haruna, M. Ohmi, T. Mitsuyama, H. Tajiri, H. Maruyama, and M. Hashimoto, *Opt. Lett.* **23**, 966 (1998).
5. L.-W. Chang, P. Y. Chien, and C.-T. Lee, *Appl. Opt.* **38**, 2843 (1999).
6. X. Z. Wang, O. Sasaki, T. Suzuki, and T. Maruyama, *Appl. Opt.* **39**, 4593 (2000).
7. D. L. Li, X. Z. Wang, X. F. Wang, L. P. Guo, and Y. M. Liu, *Chin. J. Lasers (in Chinese)* **31**, 350 (2004).