Dual-channel optical phase measurement system for improved precision

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Developments and applications of a dual-channel phase measurement system are being proposed and experimentally studied by utilizing an optical homodyne technique. In this measurement system, the phase modulation was adopted by using a near-stable Zn-indiffused lithium niobate phase modulator. The proposed method was successfully applied on the simultaneous measurements of the phase-retardation difference between a transmitted light and a reflected light after passing through a nonpolarization beam splitter. The measured stability of the phase-retardation difference was approximately 0.0013 rad. © 2008 Optical Society of America

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The schemes of optical phase modulation and intensity demodulation have been widely used in optical metrology and communication systems [1–4]. Usually, the single-polarization phase modulation is adopted in a Mach–Zehnder interferometer with a splitting-path setup. Besides, the phase-retardation modulation between two orthogonal polarizations is demonstrated in a common-path polarization interferometer. To improve the measurement precision, the sinusoidal phase modulation and interferometric signal demodulation via a Fourier analysis has been successfully demonstrated in surface plasmon resonance biosensors and displacement measurements [2–4]. Traditionally, phase modulations were achieved by electrically controlling a Pocket cell. Because of the buck crystal, the driving voltages are higher than 100 V [3]. To increase the modulation speed and make a compact module, a lithium niobate (LN) waveguide phase modulator was successfully demonstrated for application in instrumentation [5]. To avoid the photorefractive effects that disturb the phase information of an incident light, stable device operations are essential in an uncontrolled environment for a commercial instrument application [5].

In our previous work [6], a Zn-indiffused phase modulator (ZIPM) with a lower operation voltage of 10 V and a near-stable phase operation had been successfully fabricated in an *x*-cut/*z*-propagation LN substrate at a 632 nm wavelength. Besides, the single-channel phase measurement system using the homodyne technique also has been developed in the LABVIEW platform (National Instruments) [6]. To enhance a measurement precision in the optical metrology, a dual-path polarization interferometer was proposed by considering the phase variations of a sensing path and a reference path at the same time. However, the systematical errors are dependent on the path-dependent phase variations in a typical nonpolarization beam splitter (BS) used in such measurement systems [7]. In this Letter, a new method is successfully demonstrated for simultaneously measuring the phase-retardation difference between two different paths in a typical measurement setup. The novel ZIPM was used as a signal modulation in the proposed dual-channel phase measurement system. These results confirm that the proposed instrument is able to characterize the path-dependent phase retardations. The research findings indicate that the stable ZIPM can be potentially used as a compact polarization modulator for optical metrology.

Figure 1 presents a schematic of the proposed optical metrology system. A linear polarization of an incident He–Ne laser light of 632 nm is obtained by using a polarization controller consisting of a polarizer (PL1) and a half-wave plate (λ/2 WP). The polarized light at +45° with respect to the *x*-axis of the LN substrate is focused with a lens (L1) and launched into the previous reported ZIPM [6]. Then the phase delay between the TE and TM polarizations is modulated sinusoidally via the driving peak-to-peak voltage of 10 V at a frequency of 100 Hz. The output light passing through another lens (L2) and a test nonpolarization BS is divided into transmitted light and reflected light. The interferometric intensities are received by the photodetectors PD1 and PD2 after passing through the corresponding analyzers AL1 and AL2 with −45°. The output intensities of both channels are represented by $P_{\text{out}}=I_{\text{TE}}+I_{\text{TM}}+2\sqrt{I_{\text{TE}}I_{\text{TM}}}\cos[\beta\sin(2\pi ft)+\phi_{T,R}]$. I_{TE} and I_{TM} are the optical intensities of both orthogonal polarizations. They are also dependent on the azimuth angles of the polarizer and analyzer and the polarization-dependent propagation loss in the optical arrangements. The signal frequency and modulation depth of

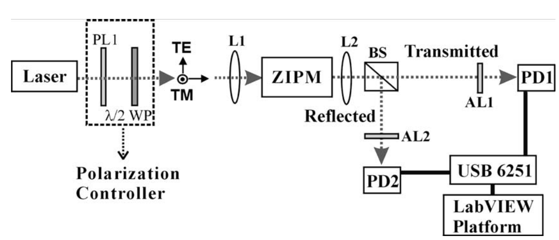

Fig. 1. Measurement setup.

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the applied voltages are represented by f and β, respectively. The notation of $\phi_{T,R}$ is represented for the phase retardations of transmitted and reflected paths. By considering the phase retardation before entering into the BS, $\phi_{T,R}$ is given as $\phi_{T,R}=\Delta\phi+\Delta\phi_{T,R}$, where $\Delta\phi$ is the static phase retardation induced in the ZIPM and $\Delta\phi_{T,R}$ is the phase retardation for the transmitted and reflected lights passing through the BS with different boundary conditions. The received intensity signals from the two photodetectors (PD1 and PD2) were connected to a laptop personal computer through a data-acquisition-box (USB 6251, National Instruments). The signal processing based on the fast Fourier transform analysis is performed by using the LABVIEW-based software (version 8.5). Figure 2 illustrates the analyzed power spectra for both transmitted and reflected lights. The analyzed spectra for different harmonic intensities are represented as follows:

$$I_1(f) = 4\sqrt{I_{\mathrm{TE}}I_{\mathrm{TM}}}\sin(\phi_{T,R})J_1(\beta), \tag{1}$$

$$I_2(2f) = 4\sqrt{I_{\mathrm{TE}}I_{\mathrm{TM}}}\cos(\phi_{T,R})J_2(\beta), \tag{2}$$

$$I_3(3f) = 4\sqrt{I_{\mathrm{TE}}I_{\mathrm{TM}}}\sin(\phi_{T,R})J_3(\beta), \tag{3}$$

where $J_k(\beta)$ is the Bessel function of order k with an index factor of β. The first, second, and third harmonics are I_1, I_2, and I_3, respectively. These parameters are used to calculate the values of β and $\phi_{T,R}$. According to Eqs. (1) and (3), β can be solved according to $I_1/I_3=J_1(\beta)/J_3(\beta)$ by using an automatic detection performed in the LABVIEW program. According to the rate between Eqs. (2) and (3), the polarization-dependent factors of I_{TE} and I_{TM} can be canceled out. After a arctan operation, $\phi_{T,R}$ can be derived as $\phi_{T,R}=\tan^{-1}[I_1J_2(\beta)/I_2J_1(\beta)]$. Therefore, the precision of measurements is mainly dependent on the resolutions of harmonic signals and β.

In a typical commercial BS, the amplitude ratios of TE polarization and TM polarization in the reflected and transmitted lights are usually different. The phase-retardation effects may induce a change in the polarization state. One of the systematic errors in measuring phase retardations is related to path-dependent polarizations (transmitted and reflected lights) [7]. To evaluate the capabilities of the proposed system, the path-dependent phase retardations passing through the BS were measured for further discussion. For statistical calculations, there are 120 data within a period of 60 s in each measurement cycle. We repeat the same measurement conditions three times to evaluate the system stabilities. Figure 3 shows the measurement results of the mean and standard deviation of a phase difference for different times. The values of the mean are 0.303, 0.31, and 0.335 rad from the first time to the third time as shown in Fig. 3(a). The values of standard deviation are 0.0013, 0.0017, and 0.0014 rad from the first time to the third time shown in Fig. 3(b). These results indicate that the proposed system is stable and precise for analyzing the phase differences among different paths.

In optical metrology, the phase retardation of an incident light was changed by using a quarter-wave plate with different azimuth angles. After the BS, we individually inserted the quarter-wave plate into the transmitted and reflected paths. The measurement stabilities of phase retardations are shown in Fig. 4(a). If only considering the phase retardations in one of two channels (square and diamond traces), the standard deviation ranges are large for different angles. However, the values of standard deviation of measured phase difference are stable for different angles when considering both channels at the same time. The phase differences are displayed by the circles when placing only the quarter-wave plate in the transmitted path. Moreover, the triangle ones are represented for only placing the quarter-wave plate in the reflected path. The average values of around 0.002 rad are independent on the angles and the locations of the wave plates. Compared with previous measurements without inserting the additional quarter-wave plate, the standard deviation has a slight increase of about 0.001 rad. Moreover, the phase difference among the dual paths can be modulated by placing the quarter-wave plate in front of the BS. The measured values of standard deviation of phase difference are around 0.0025 rad, obtained for different angles as shown in Fig. 4(b). These values are larger with than without the insertion of any quarter-wave plates. We believe that the larger standard deviation is caused by an additional multireflection between the wave plate and the BS in the optical path.

In the optical measurement, the environmental noise from a scattering light easily disturbs the measurement precision. To verify the capabilities of spectrum analysis in the proposed instrument, the measurement was further performed in a bright environment. Figure 5 presents the compared results of phase retardation and phase difference for mea-

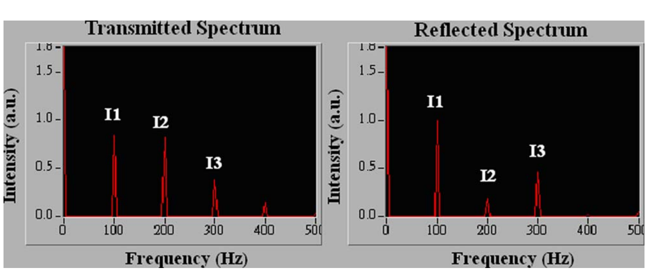

Fig. 2. (Color online) Analyzed power spectra for both transmitted and reflected lights.

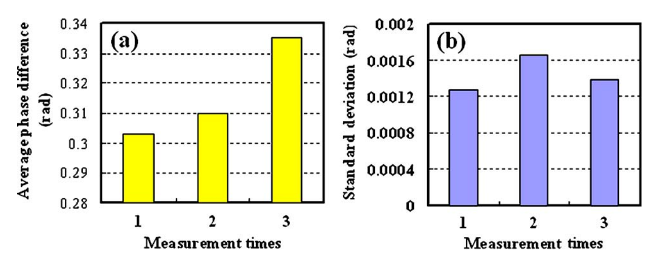

Fig. 3. (Color online) Statistical results for different times of measurements: (a) average phase difference and (b) standard deviation.

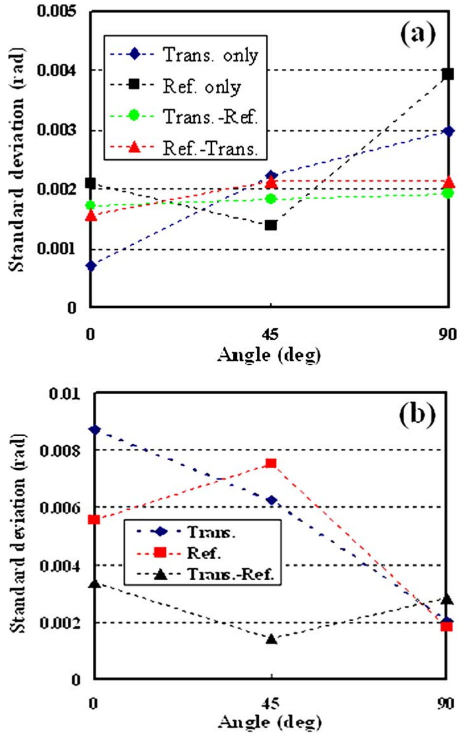

Fig. 4. (Color online) Stability measurements of phase retardations caused by different azimuth angles of a quarter-wave plate in the difference paths (a) after and (b) before the BS.

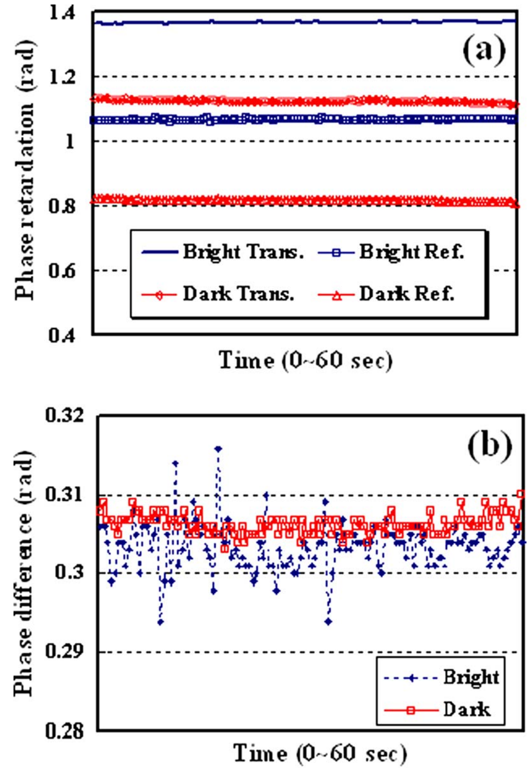

Fig. 5. (Color online) Measurement results for dark and bright environments: (a) phase retardation and (b) phase difference.

suring in dark and bright environments. The initial biases of phase retardation are different for the same measuring paths in dark and bright measurements, as shown in Fig. 5(a). By considering the phase difference between both channels, the means of phase differences are 0.303 and 0.301 rad for dark and bright measurements, respectively, as shown in Fig. 5(b). The difference of mean values is smaller than 0.002 rad. The values of standard deviation are 0.0013 and 0.0030 rad for dark and bright measurements, respectively. It is obvious that the FFT schemes decrease the sensitivity of the noise induced in the bright environment. This advantage is useful for designing a portable measurement system to use in a normal test environment. It also means that the measurement precision can be enhanced, greatly, by using the proposed dual-channel phase measurement system.

In summary, we have successfully demonstrated a dual-channel phase measurement system, for the first time, by utilizing an optical homodyne technique and a LABVIEW-based platform. The precision was improved effectively by using simultaneous measurements for two different channels. The results also show that the Zn-indiffused phase modulators can provide stable phase modulation with enough throughput powers for optical metrology at a 632 nm wavelength.

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