A MODIFIED VISIBILITY ENHANCED INTERFEROMETER FOR MEASURING ROUGH SURFACES BASED ON AN INJECTION LOCKING TECHNIQUE

Jonghan Jin[#], Yong-Bong Lee, Jae Wan Kim, Jong-Ahn Kim and Chu-Shik Kang

Korea Research Institute of Standards and Science (KRISS), 267 Gajeong-ro, Yuseoung-gu, Daejeon, 305-340, Republic of Korea, [#]jonghan@kriss.re.kr

Abstract: We have demonstrated a modified visibility enhanced interferometer based on an injection locking technique for measuring rough surfaces. Because a light is scattered by rough surfaces, the light reflected from samples in a measurement arm of the optical interferometer became weak. For enhancement of a visibility, optical intensity of the light reflected from the sample should be amplified as same as that reflected from a reference mirror. By using the injection locking technique, the weak light can be amplified while keeping the phase information. The proposed interferometer could enhance the visibility of the interference signal about 10 times.

Keywords: Interferometer, Visibility, Rough surface, Injection locking technique

1. INTRODUCTION

An optical interferometer, which can be traceable to the length standard, has been exploited for precision dimensional metrology [1-3]. For reliable measurements, interference signals should be obtained well and analyzed accurately. The interference signals can be observed clearly when the optical intensities of two separate lights reflected from both a reference mirror and a sample are nearly the same. When measuring the sample having rough surfaces, the light reflected from the sample becomes weak due to scattering. Therefore, the difference of optical intensities of lights reflected from both arms makes a poor visibility of the interference signal.

To obtain a high visibility of the interference signals, in the most laser interferometers for length measurement, two mirrors are usually used in both arms to maintain the optical intensities of them. However, when measuring rough surface or low reflective surface such as glasses, color filters and roughly polished parts, the visibility of interference signal is degraded seriously due to unbalanced optical intensities of both arms [4].

In this paper, we have modified the novel interferometer proposed by KRISS (Korea Research Institute of Standards and Science) for measuring samples having rough surface. It is operated by amplifying a weak light reflected from a sample having a low reflectance with the help of the injection locking technique [5]. The injection locking technique can amplify the weak light while maintaining a phase value that contains length information.

2. BASIC PRINCIPLE

Visibility, V was defined as the strength of interference. It is also called the modulation depth of the contrast of the interference signal. It depends on optical intensities reflected from a reference mirror and a sample, I_r and I_s, which can be expressed by

$$V = \frac{2\sqrt{I_r I_s}}{I_r + I_s} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

where, I_{max} and I_{min} represent the maximum and minimum optical intensities of the obtained interference signal, respectively.

When the intensities reflected from the reference mirror and the sample are exactly same, $I_r = I_s$, the visibility becomes 1, the largest value. If the intensity from the sample, I_s, becomes weak, the visibility approaches 0, the smallest value. When the visibility, V, approaches close to 1, the interference signal becomes clear, which is required for reliable measurements. However, when the visibility is 0, the interference signal is difficult to be observed clearly. Therefore, for reliable measurements, the visibility should be enhanced enough.

In order to enhance the visibility, the light reflected from the sample having a low reflectance should be amplified to have the same optical intensity or at least similar optical intensity as that reflected from the reference mirror. Otherwise, the optical intensity of light in the reference arm should be reduced to match the optical intensity of the light reflected from the sample. In the latter case, the interference signals sometimes could not be detected because of its low optical power. In addition, whenever measuring a sample having several materials having its own reflectance, the intensity of each arm should be adjusted carefully to enhance the visibility of the interference signal.

By using the injection locking technique, the optical intensity of a seed laser can be amplified. For using the technique in the optical interferometer, the phase difference between the seed laser and a slave laser, a secondary light

source, should be considered carefully. A deviation of the phase differences is a sort of phase noises, which can cause measurement errors seriously. It could even lose all phase information of samples. According to the previous work reported [10], the phase difference, $\Delta\varphi$, can be expressed by

$$\Delta\varphi = \sin^{-1}(\Delta\nu/\Delta\nu_L) - \tan^{-1}\alpha \qquad (2)$$

where, $\Delta\nu$ is a frequency difference between the seed laser and the slave laser, $\Delta\nu_L$ is an injection locking range and α is a line-width enhancement factor, which is a constant having a value of 3 to 7 for semiconductor lasers [11, 12]. A constant phase difference is not a factor to be considered for optical interferometers because it just corresponds to a fixed additional optical path.

However, a time varying phase difference can affect measurement results seriously. The fluctuation of phase difference, $\delta\Delta\varphi$, is proportional to control noise of the driving current of the slave laser, δI, directly under the following conditions; (1) frequency difference between the seed laser and the slave laser is much less than the injection locking range, $\Delta\nu/\Delta\nu_L \ll 1$, (2) frequency of the slave laser is proportional to the driving current, I, and (3) temperature is stabilized. From eq. (2), the fluctuation of phase difference is given by [6-10]

$$\delta\Delta\varphi = \gamma \cdot \delta I/\Delta\nu_L \qquad (3)$$

where, γ is a proportional constant.

3. EXPERIMENTS AND RESULTS

Fig. 1 Optical layout of the measurement system (C: circulator, L: lens)

Figure 1 shows the optical layout of the overall system. Distributed feedback lasers were adopted as the light source (the seed laser) and the secondary light source (the slave laser). They have the center wavelength of about 1542.30 nm with the optical power of about 10 mW. The frequency stability was estimated as $\sim 10^{-8}$ at 1 s. The interferometer part has two separated arms; one is for reference and the other is for the sample. In the reference path, the light

collimated by a lens and then reflected by a metal coated mirror having a reflectance of more than 0.99. The mirror in the reference arm was modulated by a precision stage driven by a PZT actuator along the optical axis. The optical delay line was inserted in the reference arm to adjust the optical path difference between two paths, the reference path and the measurement path. In the other path, measurement path, the light was delivered to the target through an optical coupler and a circulator.

The reflected light from the sample was weak due to scattering on the rough surface of the sample. It was injected into a secondary light source. The optical power of the injected light was enhanced enough for good visibility of the interference signal. The generated interference signal was obtained by a photo-detector. For the secondary light source, an optical isolator attached on the slave laser was removed for the injection locking. To observe the interference signals, the reference mirror was modulated by a ramp input having a travel of 30 μm with a rate of 0.1 Hz. Roughly polished surface of a metal plate having a reflectance of about 0.01 was adopted as the sample. The interferometer was constructed by optical fibers shown as Fig. 2. Figure 2 shows the photographical view of the experimental setup.

Fig. 2 Photographical view of the experimental setup

Since an optical amplification was performed only in the measurement path using the injection locking technique, the phase variation in the injection locking process should be considered carefully as mentioned before. The constant phase delay is a not problem, which is only a fixed additional optical path. On the other hand, the time-varying fluctuation of phase delay can distort the interference signal including information of positions of the sample. Therefore, the time-varying fluctuation of phase delay should be removed or minimized for reliable measurement.

The fluctuation of phase delay, $\delta\Delta\varphi$, depends on the stability of driving current of the secondary light source, which could be determined by eq. (3) under temperature stabilization. In our experiments, the injection locking range, $\Delta\nu_L$, was measured as ~ 8 GHz in frequency or 0.07 nm in wavelength. The proportionality constant of the secondary light source, γ, was estimated to be 0.57 MHz/mA, which equals 4.5 pm/mA in a wavelength term. The resolution of

the driving current controller in use was 1 μA with a typical noise of less than 1.5 μA. Therefore, the time varying phase shift was estimated to be ~10^{-4} rad, which corresponds to less than 0.1 nm in length at the center wavelength of 1542.30 nm. Because the time varying phase difference term was relatively small, it could be neglected. Moreover, the time varying phase difference term can be removed easily using a low pass filter even if it is larger because the frequency of the time varying phase shift term is extremely high. It means the effect of phase difference can be ignored in general cases.
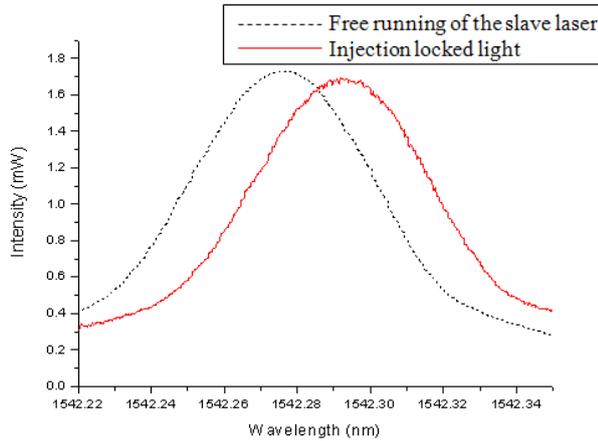
Fig. 3 Spectrums of the slave laser under free running and the injection locked light

To confirm the state of the injection locking, the frequency shift was observed in spectral domain. Figure 3 shows two optical spectrums, free running of the secondary light source (slave laser) and the injection locked light (slave laser after the injection locking). The injection locked light has a wavelength of ~1542.295 nm, which is the exactly same wavelength as the light source in use (seed laser). Wavelength difference between the seed laser and the slave laser was ~ 0.025 nm, which corresponds to ~ 3 GHz in frequency. Amount of the wavelength difference was large enough to detect by using a conventional optical spectrum analyzer (OSA). When light reflected from the sample was injected into the secondary light source (slave laser), the wavelength of the secondary light source in free running shifted to that of the seed laser. It could be observed as shown in Fig. 3. By blocking the measurement arm to remove the seed laser, the optical spectrum of the slave laser was observed.

In Fig. 4(a), the black line having large amplitude represents an optical interference signal obtained by the proposed interferometer when measuring the sample having a low reflectance of about 0.01. The optical interference signal obtained by a general Michelson's type interferometer without the secondary light source is shown as the red line having small amplitude in Fig. 4 (a).

The bottom blue line in Fig. 4(a) is an input signal of a PZT amplifier to oscillate the reference mirror. According to eq. (1), the visibility of the interference signal obtained by the proposed interferometer was about 0.7, and that obtained by the general Michelson's type interferometer was 0.06.

Therefore, the proposed interferometer could enhance the visibility of the interference signal at least 10 times. Figure 4(b) shows an enlarged picture of the interference signals in the range of 11 s to 12 s in Fig. 4(a).
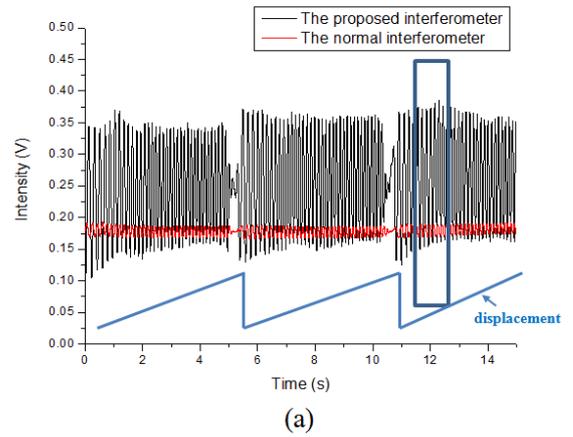

(a)
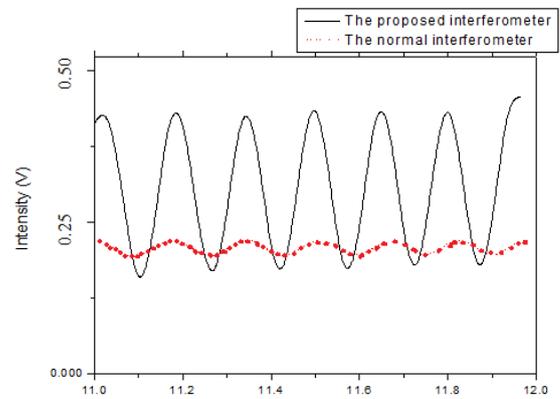
(b)

Fig. 4 Interference signals obtained by the proposed interferometer and the normal interferometer; the bottom line (blue) of Fig. 4(a) represents for the displacement of the reference mirror.

Figure 5 shows interference patterns obtained by the general Michelson's type interferometer and the proposed interferometer. The interference pattern obtained by the general Michelson's type interferometer was not clear because of a low visibility of 0.06. The interference pattern obtained by the proposed interferometer was clear relatively with the visibility of 0.7.
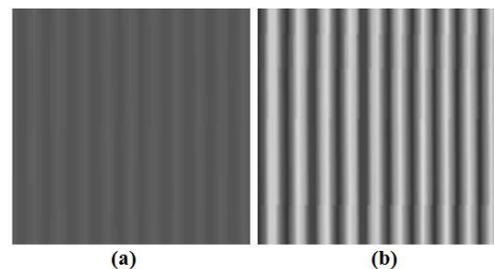

(a)   (b)

Fig. 5 Interference patterns obtained by (a) the general Michelson's type interferometer and (b) the proposed interferometer.

4. FUTURE APPLICATIONS

Precision calibration of accelerometers having rough surfaces can be one of the possible applications because the visibility enhanced interferometer can measure the displacement of samples having a low reflectance. The accelerometer is a device converting mechanical vibrations into electric signals. The sensitivity, the most important factor to evaluate performance of the accelerometer, is defined as the ratio of amplitudes of input vibrations and electric output signal. To determine the sensitivity of accelerometers, the amplitudes and phases of their electric output signals should be measured while shaking accelerometers with well-defined sinusoidal frequencies. At the same time, the displacements of the accelerometers under test also should be measured by using a laser interferometer.
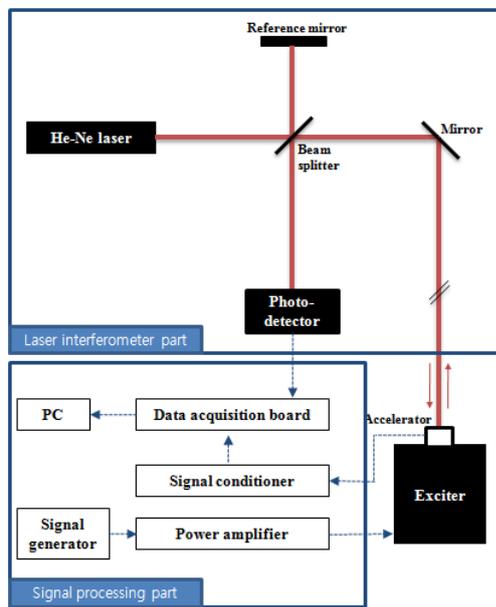
(a) Block diagram of precision calibration system

(b) Photographic view of the calibration system
Fig. 6 Precision calibration system of accelerometers

By comparing with the waveforms obtained by the laser interferometer and the accelerometer's output signals itself, the sensitivity of the accelerometer can be determined in terms of amplitude and phase. The obtained waveforms can be estimated by using a sine-approximation method [13-15]. The amplitude sensitivity can be determined by comparing the displacement of the accelerometer and voltage amplitude of the output electric signal of the accelerometer. The phase sensitivity can be determined by a phase lag, which is phase shift between the output electric signal and the input vibration.

Figure 6 (a) shows the block diagram of precision calibration system for accelerometers. It consists of three parts of the laser interferometer part, an exciter, and a signal processing part. The laser interferometer part is to measure the displacement of the accelerometer installed on the top surface of the exciter. Michelson's interferometer type have been adopted generally with a stabilized He-Ne laser having a centre wavelength of 632.8 nm. The photographic view of the calibration is shown in Fig. 6 (b)

In calibration process, the plane mirror having a reflectance of more than 0.99 should be attached on the top surface of the accelerometers because the surface roughness is not good enough to reflect the incident light even if they have been polished. The attached mirror might lead some errors by changing mass of the accelerometers in the calibration process. The resonance frequency of the accelerometer also might be shifted slightly. Therefore, the mass of the plane mirror can be an additional measurement uncertainty factor.

By replacing the laser interferometer part with the visibility enhanced interferometer, the plane mirror attached on the accelerometer can be removed. That means the uncertainty component caused by additional mass of the plane mirror can be eliminated. In the near future, the precision calibration system for accelerometers based on the visibility enhanced interferometer will be studied and designed in KRISS.

5. SUMMARY

The visibility enhanced interferometer based on the injection locking technique was proposed and demonstrated. The modified interferometer works well even if the target has roughly polished surfaces. When the reflectance of the sample was even less than 0.1 due to scattering at the rough surface, the visibility of the interference signal obtained by the suggested interferometer was enhanced at least 10 times better than that obtained by the general Michelson's type interferometer. The interference signal was also observed clearly by the proposed method, which was good enough for reliable measurements.

It can be expected to expand applicable areas for detecting vibrations of objects having roughly polished surfaces and transparent materials in the various industrial fields such as semiconductor and flat panel display. For standard measurement in KRISS, the precision calibration for accelerometers will be the one of the useful applicable candidates.

6. REFERENCES

[1] K. M. Khavinson, "Ring interferometer for two-sided measurement of the absolute lengths of end standards," Applied Optics, Vol. 38, No. 1, pp. 126–135, 1999.

[2] J. Jin, Y.-J. Kim, Y. Kim, S.-W. Kim, and C.-S. Kang, "Absolute length calibration of gauge blocks using optical comb of a femtosecond pulse laser," Optics Express, Vol. 14, No. 13, pp. 5968–5974, 2006.

[3] J. Jin, J. W. Kim, C.-S. Kang, J.-A. Kim, and T. B. Eom, "Thickness and refractive index measurement of a silicon wafer based on an optical comb," Optics Express, Vol. 18, No. 17, pp. 18339–18346, 2010.

[4] Y.–B. Lee, H. C. Kim, and S.-W. Kim, "Determination of the sensitivity phase of an accelerometer based on an analysis of the harmonic components of the interference signal," Measurement Science and Technology, Vol. 19, pp. 045204, 2008.

[5] J. Jin, J. W. Kim, C.-S. Kang, J.-A. Kim, "Visibility enhanced interferometer based on an injection-locking technique for low reflective materials," Optics Express, Vol. 18, No. 23, pp. 23517–23522, 2010.

[6] G. R. Hadley, "Injection locking of diode lasers," IEEE Journal of Quantum Electronics, Vol. QE-22, No. 3, pp. 419–426, 1986.

[7] R. Lang, "Injection locking properties of a semiconductor laser," IEEE Journal of Quantum Electronics, Vol. QE-18, No. 6, pp. 976–983, 1982.

[8] G. H. M. van Tartwijk and D. Lenstra, "Semiconductor lasers with optical injection and feedback," Quantum Semiclass Optics, Vol. 7, pp. 87–143, 1995.

[9] L. Zhang, R. Dou, and J. Chen, "Characteristics of the injection-locked master-slave lasers," Applied Optics, Vol. 47, No. 14, pp. 2648–2654, 2008.

[10] F. Mogensen, H. Olesen, and G. Jacobsen, "Locking conditions and stability properties for a semiconductor laser with external light injection," IEEE Journal of Quantum Electronics, Vol. QE-21, No. 7, pp. 784–793, 1985.

[11] J. Ohtsubo, "Semiconductor Lasers: Stability, Instability and Chaos," 2nd edition, pp. 32–33. Springer, 2008.

[12] Y. Yu, G. Giuliani, and S. Donati, "Measurement of the linewidth enhancement factor of semiconductor lasers based on the optical feedback self-mixing effect," Photonics Technology Letters, Vol. 16, No. 4, pp. 990–992, 2004.

[13] Y. B. Lee, S. Jung, and J. Jin, "Precision Phase Calibration System of Accelerometers," Journal of the Korean Soceity for Precision Engineering, Vol. 28. No. 5, pp. 585-590, 2011.

[14] ISO 16063-1, "Methods for the calibration of vibration and shock transducers: Part I. Basic concepts," 1998.

[15] ISO 16063-11, "Methods for the calibration of vibration and shock transducers: Part II. Primary vibration calibration by laser interferometer," 1998.