Investigation of a signal processing method based on a dual-detection chromatic confocal probe

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A signal processing method based on a dual-detection confocal probe, which is referred to be tracking intersection (TI) method, is investigated in this paper. Chromatic confocal probe employing a mode-locked laser as a light source has been developed for surface profile precise measurements. The chromatic confocal probe can measure the linear displacement by employing a signal processing method, which is referred to be tracking local-minimum (TL) method, for a pair of confocal response curves from a dual-detection units. However, the output from the TL method has an asymmetric response curve, which is one of the main reasons of the measurement accuracy. The reason for the asymmetric response is due to the shape of the local-minimum point position at which the TL method in the confocal responses. Therefore, an intersection point of the confocal response curves are employed as a signal processing point instead of the local-minimum point in this paper. TI method is investigated to improve the measurement accuracy of the dual-detection confocal probe based on a numerical and experimental considerations.

NOMENCLATURE

I_{Mea} = A light spectrum obtained from a reflected light from a target surface without a detector offset.
I_{Ref} = A light spectrum obtained from a reflected light from a target surface with a detector offset.
I_{Mea} = A normalized light spectrum by dividing I_{Mea} by I_{Ref}
z_d = A detector offset

1. Introduction

Non-contact measurement of a three-dimensional (3D) surface profile is important task to assure the quality and the performances of objects having small features such as MEMS devices or semiconductor devices [1,2]. Mainly 3D surface profile is obtained by combing a heigh measurement mechanism and a place scanning mechanism [3,4]. The main height measurement mechanisms are contact probes and non-contact measurement. Since recent measurement objects are fragile and there is no need to worry about damaging the surface, non-contact probes have been required after in recent years [5]. In addition, measuring instruments having a sub-micrometric resolution and stability in the Z-direction are required.

Confocal microscopy is one of the non-contact probes employing a focused beam as optical probe, which is referred to be as a confocal probe [6,7]. An optical setup of the confocal probe is composed of a point source and a point detector. The light from the point source is focused on a sample surface and the reflected light is then captured by the point detector. In this setup, a high axial resolution and high contrast measurement can be realized since the out-of-focus light rays can be eliminated by these pinhole [8-11]. One of the major confocal probe types is chromatic confocal probe employing a mode-locked laser as a light source [10] since the mode-locked laser make it possible to non-scanning Z-displacement measurement and high in-plane resolution measurement due to the features of a laser having a wide range optical spectrum. On the other hand, non-smoothness light source spectrum shape influences the measurement accuracy [12,13]. Therefore, Chen et al. proposed a dual-detection chromatic confocal probe and a signal processing, which is referred to be as a tracking local-minimum (TL) method to eliminate not only the influence of the non-smoothness light spectrum shape but also a transmittance and/or reflectance of the measurement target and optical components [14,15]. The dual-detection chromatic confocal probe acquired the measurement light spectrum I_{Mea} and the reference light spectrum I_{Ref} from the reflected light from the measurement surface, and then obtained a normalized output I_{TLM} by dividing I_{Mea} by I_{Ref} based on the TL method. However, the I_{TLM} had an asymmetrical optical spectrum, which is an error factor in peak wavelength detection, resulting in low measurement accuracy.

Therefore, in this paper, a investigation of a signal processing method based on a dual-detection chromatic confocal probe for enhancing the measurement accuracy. Experimental comparisons of TL methods are conducted to determine their superiority.

2. Dual-detection chromatic confocal probe

2.1 A problem of the conventional Tracking local-minimum method

The figure 1 shows a schematic diagram of the dual-detection chromatic confocal probe. A mode-locked laser is guided to the optical setup by a single mode fiber, and then illuminated on an optical path. The illuminated light is collimated by an objective lens and passes through a polarized beam splitter (PBS) and a quarter wave plate (QWP). The light is focused on a target surface. The reflected light is focused on an edge surface of a single mode fiber just after being divided into two lights. It should be noted that one of the lights, which is referred to be as a measurement light, is captured by a single mode fiber with a detector offset z_d and the other of the lights, which is referred to be as a reference light, is captured by another single mode fiber. Analyzed measurement light spectrum I_{Mea} and reference light spectrum I_{Ref} have a peak shift due to the detector offsets as shown in Figure 1(a) [14,15]. The TL method carries out to divide the measurement light spectrum I_{Mea} by reference light spectrum I_{Ref} and generates a normalized output I_{TLM} as shown in Figure 1(b). The peak wavelength of the I_{TLM} is coincide with the first local-minimum-point wavelength of the I_{Ref}. The local minimum point is changed by the Z-displacements of the target surface. This means that the Z-displacement can be obtained by tracking the peak wavelength the I_{TLM} [14]. It should be noted that the I_{Mea} and I_{Ref} have a same influence of the light spectrum shape, and the influences can be eliminated by the signal processing based on the TL method as following equation [14,15]:

$$I_{TLM} = \frac{I_{Mea}}{I_{Ref}}. \quad (1)$$

However, the shape of the I_{TLM} is asymmetry since the shape of the local-minimum point of the I_{Ref} is also asymmetry. And since the intensity of the local-minimum point is very low, the shape of the I_{TLM} is easily affected by the noise. Therefore, the TL method has a low measurement accuracy.

2.2 A investigated Tracking intersection method

Figure 1(c) shows a tracking intersection (TI) method to be investigated in this paper. Unlike TL method, the TI method detects the intersection of I_{Mea} and I_{Ref} as the peak of the normalized output I_{TIM} as following equation:

$$I_{TLM} = \frac{I_{Mea} + I_{Ref}}{|I_{Mea} - I_{Ref}|}. \quad (2)$$

By detecting the intersection of I_{Mea} and I_{Ref} as the peak of I_{TIM}, it is possible to detect a sharper peak than with the TL method, thereby reducing the impact of spectral asymmetry on the accuracy of z-

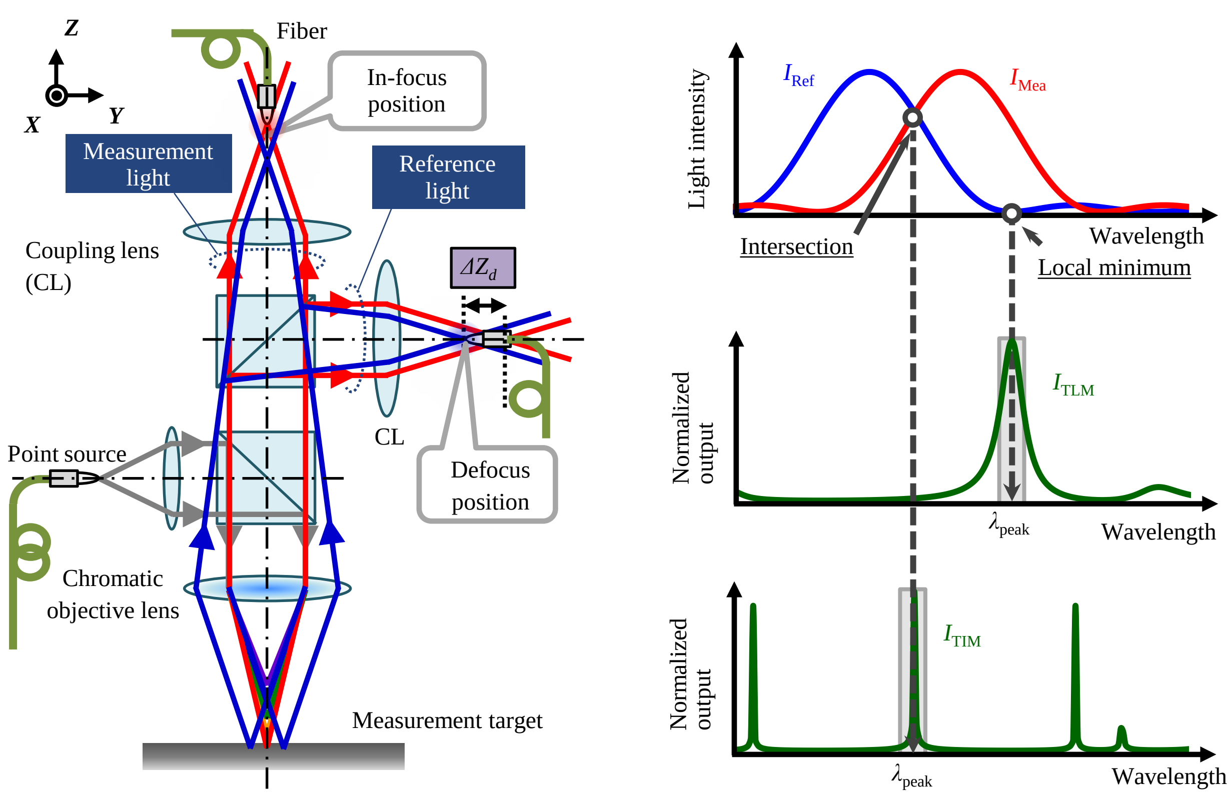

Fig. 1: A schematic diagram of the dual-detection chromatic confocal probe: (a) A measurement light spectrum I_{Mea} and a referemce light spectrum I_{Ref}, (b) a normalized output I_{TLM} based on the tracking local-minimum method, (c) a normalized output I_{TIM} based on the tracking intersection method

position measurement. In addition, the intensity of I_{Mea} and I_{Ref} at the intersection is stronger than the intensity at the local-minimum point of I_{Ref}, thus reducing the effect of noise.

3. Experimental comparison of the TL method and TI method

Figure 2 shows the experimental setups. A commercial mode-locked laser (C-Fiber BA Side (Menlo Systems GmbH)) are employed as a light source. The source wavelength range was from 1460 nm to 1640 nm. The laser was focused onto a measurement target surface by a chromatic lens (#67-484 (Edmund Optics Japan Co.)). A flat mirror is utilized as a measurement target having a flat surface. The flat mirror is placed on a linear stage and scanned along to Z-axis for the purpose of acquiring a relationship between the peak wavelength and z-displacement of the mirror. The scanning interval of the stage was 2 μm steps, and the measurement light spectrum I_{Mea} and the reference light spectrum I_{Ref} were acquired at each position. It should be noted that the measurement light source I_{Mea} is captured by a detector 1 composed of an objective lens L1 and a single mode fiber without a detector and the reference light source I_{Ref} is captured by a detector 2 composed of an objective lens L2 and a single mode fiber with a detector offset z_d, which is set as be 80 μm.

Figure 3 shows obtained spectra at a z-displacement. Figure 3(a) illustrated that a measurement light spectrum I_{Mea} and a reference light source I_{Ref}. As can be seen Figure 3(a), The shapes I_{Mea} and I_{Ref} were affected by the non-smoothness light spectral shape of the light source, indicating that the peak is not easily detected in both spectra. Here, A point means a local-minimum point of the I_{Ref} and B point means a intersection point between I_{Mea} and I_{Ref}. In this case, Figure 3(b) shows a normalized output I_{TLM} based on the tracking local-minimum method and a normalized output I_{TIM} based on the tracking intersection method, respectively. It can be seen that the spectrum shape of the I_{TLM} was asymmetric shape while that of the I_{TIM} was symmetric shape. In addition, it was also realized that the full width at half maximum (FWHM) of the I_{TLM} was evaluated as 11.4 nm, which was larger than that of the I_{TIM}.

Figure 4 illustrates that comparison of FWHM values obtained at each z-position. The mean value of FWHM in I_{TLM} was 6.75 nm, whereas the mean value of FWHM in I_{TIM} was 0.48 nm. These results indicated that the measurement accuracy and measurement resolution of the TL method was better than that of TI method.

The measurement range based on each TL method and TI method were also evaluated. The results, showing the peak wavelengths obtained at each z-measurement position, are shown in Figure 5. Here, Figure 5(a) shows the result based on the TL method and Figure 5(b)

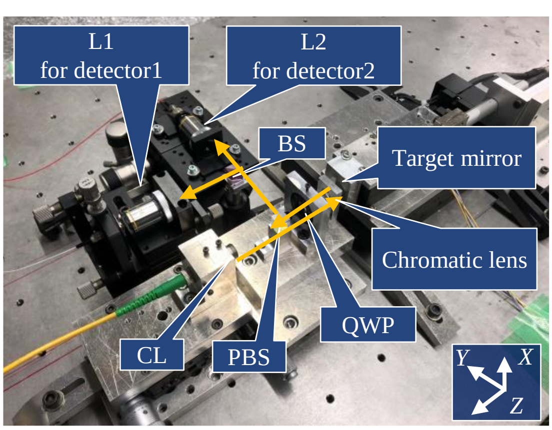

Fig. 2: A photograph of a experimental setup of the dual-detection chromatic confocal probe.

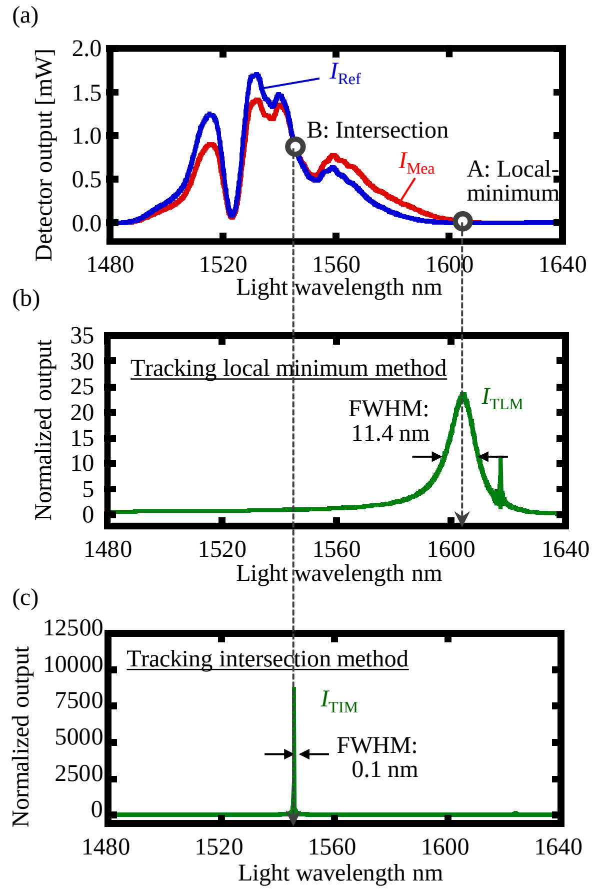

Fig. 3: Experimental results: (a) Obtained spectra of I_{Mea} and I_{Ref} at a z-displacement, (b) A normalized output I_{TLM} and (c) A normalized output I_{TIM}.

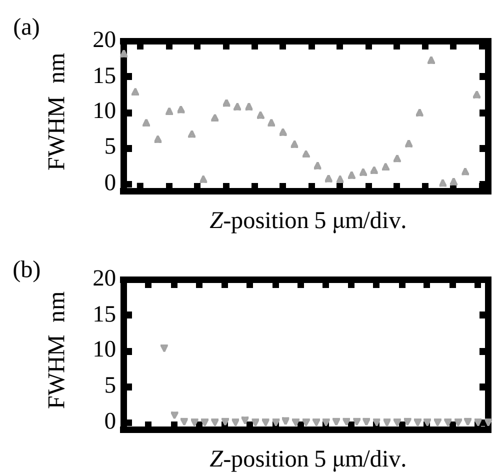

Fig. 4: (a) the full width at half maximum (FWHM) of the I_{TLM}, (b) the FWHM of the I_{TIM}

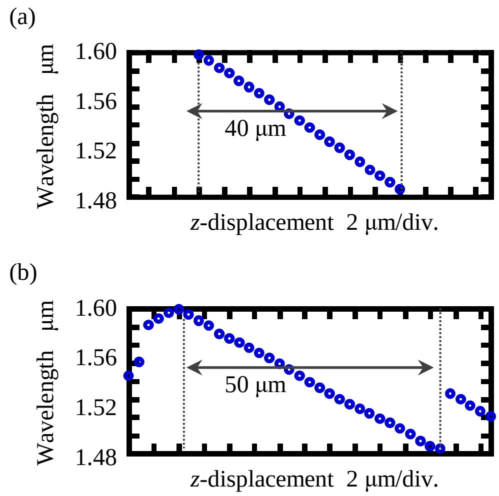

Fig. 5: Measurement range comparison between (a) TL method and (b) TI method.

shows the result of based on the TI method. Comparison of Figures 5(a) and 5(b) shows that the 50 µm measurement range obtained with the TI method is larger than the 40 µm range obtained with the TL method. On the other hand, in Figure 5(b), it was confirmed that there were multiple z-positions showing the same peak wavelength. This was due to the existence of multiple intersection points of I_{Mea} and I_{Ref}, as shown in Figure 1(c). This effect means that the TI method is more complicated than the TL method in terms of the signal processing algorithm used to convert from peak wavelength to z-position. To take full advantage of the superiority of the TI method over the TL method in terms of measurement resolution, accuracy, and measurement range, it is necessary to solve the complexity of signal processing, and this consideration will be carried as a future work.

4. Conclusions

Confocal probes as optical probes that enable non-contact measurement of three-dimensional surface topography employing a mode-locked femtosecond laser as a light source have been introduced. We have summarized the problems in the TL method, which is a signal processing method that solves the cause of measurement accuracy degradation when a mode-locked laser is used as a light source. Then, the TI method has been investigated as a solution to the problems. Experimental comparison of the TL and TI methods has realized that the TI method is superior in terms of measurement accuracy, resolution, and measurement range. On the other hand, the signal processing algorithm at the TI method to convert from peak wavelength to z-position have been confirmed to have complexity.

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