Chromatic confocal microscopy with a novel wavelength detection method using transmittance

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Abstract: Chromatic confocal microscopy (CCM) is a promising technology that enables high-speed three-dimensional surface profiling without mechanical depth scanning. However, the spectrometer, which measures depth information encoded by axial color, limits the speed of three-dimensional imaging. We present a novel method for chromatic confocal microscopy with transmittance detection. Depth information can be instantaneously obtained by the ratio of intensity signals from two photomultiplier tubes by detecting a peak wavelength using transmittance of a color filter. This non-destructive and high-speed surface profiling method might be useful in many fields, including the semiconductor and flat panel display industries, and in material science.

OCIS codes: (120.6650) Surface measurements, figure; (180.6900) Three-dimensional microscopy; (180.1790) Confocal microscopy.

References and links

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#182608 - $15.00 USD Received 2 Jan 2013; revised 29 Jan 2013; accepted 25 Feb 2013; published 5 Mar 2013

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1. Introduction

The demand for fast three-dimensional (3D) microscopy has been growing in many industrial fields, including the manufacturing process of semiconductors and flat panel displays [1]. Optical methods enable non-destructive and non-contact 3D surface profiling with high-resolution and high-speed [2]. Various optical methods of surface profiling have been developed and are currently used in many industrial applications. The optical triangulation method and Moiré interferometry have the ability for high-speed imaging over a large field of view with depth resolution up to a few micrometers [2, 3]. White light interferometry provides nanometer depth resolution, but the surface profiling speed is not as fast due to the need for mechanical axial scanning [4]. Confocal scanning microscopy provides sub-micrometer resolution with high-speed surface profiling, however 3D speed is still limited due to mechanical axial scanning [5]. Differential confocal microscopy provides very high axial resolution at nanometer level and the common noise is suppressed, however the measurement range is limited [6, 7]. Since many industrial applications require real-time 3D surface profiling with simultaneous high resolution, a technical breakthrough needs to be made to fulfill this requirement.

Chromatic confocal microscopy (CCM) was developed to eliminate the mechanical depth scanning that is required for constructing 3D images in conventional confocal microscopy and thus has the capability to enhance surface profiling speed. In early studies, the concept of CCM was introduced by Molesini et al. [8] and by Boyde [9]. Then, the method for depth measurement with the use of axial chromatic aberration was applied to confocal microscopy [10–12]. With CCM, polychromatic light from a broadband light source, such as a supercontinuum laser or Xenon lamp, is configured such that each color has a different focal length due to the axial chromatic dispersion of the objective lens. By acquiring the spectrum of the returning light through the confocal aperture, depth information of the sample is achieved without mechanical depth scanning. In order to acquire the spectrum, CCM often uses a spectrometer that consists of a grating, a lens, and a line array detector [13–16]. However, acquisition speed of the line camera limits the CCM frame rate. A high-speed tunable laser can be used instead of a broadband source [17, 18], but acquisition speed is still not adequate to fulfill industrial requirements for total inspection. Thus, a new approach for acquiring depth information is needed to significantly improve CCM measurement speed.

In this study, we propose a novel chromatic confocal microscope and transmittance detection method using an optical filter. While utilizing the same basic concept of an axial chromatic aberration as previously presented, depth information is acquired by use of the optical filter instead of using dispersion grating and a line array detector. The optical filters selectively transmit or block light according to the wavelength, thus transmittance of the optical filter is dependent on the incident light wavelength. Consequently, by measuring transmittance of the reflected light from the sample through the confocal aperture, we can accurately calculate the wavelength of the light, in which depth information of the sample is encoded by the axial chromatic aberration. Since the transmittance of light can be measured much faster than the whole spectrum, the proposed method has great potential for ultrahigh-speed 3D surface profiling.

#182608 - $15.00 USD Received 2 Jan 2013; revised 29 Jan 2013; accepted 25 Feb 2013; published 5 Mar 2013

2. Principles

2.1 Principle of the chromatic confocal microscope with a transmittance detection method

The principle of the proposed chromatic confocal microscope with a high-speed transmittance detection method is illustrated in Fig. 1. The polychromatic light from a broadband light source is focused by the objective lens that is designed to have a large axial chromatic aberration. Due to the various focal lengths according to wavelength, a vertical line with rainbow-color is formed at the object space. Reflected light from the sample is then directed to the pinhole after being reflected by the beam splitter. Light with a specific wavelength, which forms a focal point on the sample surface, passes through the confocal pinhole. The remaining light with other wavelengths that form focal points off of the sample surface is blocked by the pinhole. Thus, we can measure the height of the sample by analyzing the color of the returning light. The peak wavelength that corresponds to the height of the sample needs to be identified. Generally, finding the peak intensity in the returning light spectrum can be done using a spectrometer, which consists of a diffraction grating and a line array detector. Here, we propose a high-speed transmittance detector that consists of a beam splitter, an optical filter, and two photomultiplier tubes (PMTs). We can measure the peak wavelength of the returning light from the transmittance of the optical filter obtained by the ratio of the two PMTs.

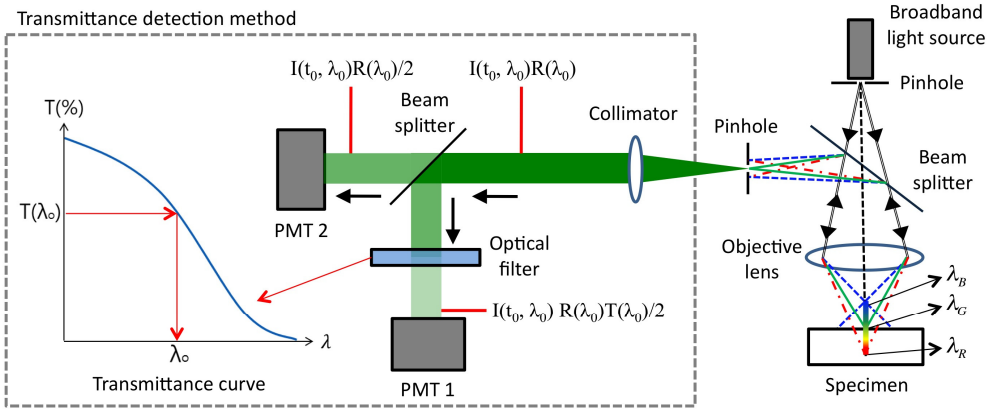

Fig. 1. Schematic of the chromatic confocal microscope with a transmittance detection method.

An example of an optical filter transmittance curve is in Fig. 1. The transmittance, T, is a function of the wavelength of the returning light, λ. If the function is one-to-one (i.e. each wavelength corresponds to a unique transmittance) the wavelength of the returning light can simply be measured by transmittance of the optical filter. The returning light intensity reflected from the sample surface with a reflectance of $R(\lambda_0)$ is $I(t_0, \lambda_0)R(\lambda_0)$, with a wavelength, λ_0, at a time, t_0. It is divided into two beams by the 50:50 beam splitter. One beam is directly detected by PMT2, while the other beam is transmitted through the optical filter and then detected by PMT1. Assuming the beam splitter is loss-free, the beam intensity at PMT2 becomes $I(t_0, \lambda_0)R(\lambda_0)/2$. The intensity of the beam through the optical filter is multiplied by the transmittance of the optical filter, becoming $I(t_0, \lambda_0)R(\lambda_0)T(\lambda_0)/2$. Thus, the ratio of the two intensity signals from the PMTs provides the transmittance of the optical filter as:

$$\frac{I_{PMT,1}}{I_{PMT,2}} = \frac{I(t_0,\lambda_0)R(\lambda_0)T(\lambda_0)/2}{I(t_0,\lambda_0)R(\lambda_0)/2} = T(\lambda_0). \qquad (1)$$

Equation (1) implies that the wavelength of the incident light is also a function of the transmittance when the incident light has a narrow band under the assumption that the function is one-to-one. Since the transmittance can be measured by the PMTs, which have a

#182608 - $15.00 USD Received 2 Jan 2013; revised 29 Jan 2013; accepted 25 Feb 2013; published 5 Mar 2013

very high frequency response up to hundreds of Megahertz, the detection speed of the peak wavelength can be significantly increased compared to linear-array based spectrometers. Furthermore, by calculating the intensity ratio, measurement error related to sample reflectance, color heterogeneity, intensity fluctuation, and common noise is minimized.

2.2 Depth measurement process

Figure 2 illustrates the depth measurement process. Depth information is encoded by the wavelength due to the axial chromatic aberration and the confocal pinhole aperture as depicted in Fig. 2(a). The axial chromatic aberration of the objective lens can be designed to have a linear relationship between the wavelength and the effective focal length. A color filter can be designed or selected so that the relationship between the wavelength and transmittance is a one-to-one function as shown in Fig. 2(b). Since sample depth is a function of the peak wavelength of the returning light through the pinhole and the wavelength is a function of the optical filter transmittance, depth is a function of the filter transmittance as shown in Fig. 2(c). In short, we can measure the height of the sample by simply measuring transmittance of the returning light.

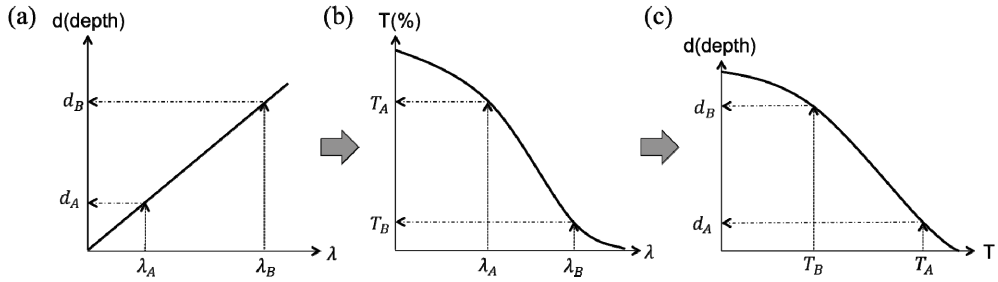

Fig. 2. Depth measurement process. (a) Depth information encoded by the wavelength due to axial chromatic aberration. (b) Dependence of color filter transmittance on the wavelength. (c) Depth information measured by the transmittance of the color filter.

3. System design

3.1. Schematic of the experimental setup

A schematic diagram of the experimental setup of the chromatic confocal microscope with the transmittance detection method is shown in Fig. 3. The collimating lens was used to collimate the light from the broadband source. Using a band-pass filter, a specific wavelength range was selected from 500 to 600 nm in which the Xenon lamp has uniform illumination. The beam was p-polarized by a linear polarizer (NT47-101, Edmund Optics). The linear polarizer, a quarter-wave plate (QWP, NT46-558, Edmund Optics), and a polarizing beam splitter (PBS, NT48-999, Edmund Optics) were used to enhance reflection light efficiency. After transmitting through the PBS and QWP, the beam was reflected by a galvanometer mirror (6210H, Cambridge Technology), which scans in the x-direction. The scan lens and the tube lens relayed the beam onto the back aperture of the objective lens with an appropriate magnification. The objective lens focused light with various focal lengths corresponding to the wavelengths. Position of the object was controlled by a motorized stage (KS101-20HD, Suruga Seiki). Reflected light from the sample traveled back through the objective lens, the tube lens, the scan lens, the galvanometer mirror, and then the QWP. Since the reflected beam changed the polarization status to s-polarization due to the QWP, it was then reflected by the PBS and focused by the collecting lens onto the pinhole. Only the light with the specific wavelength that corresponded to the height of the sample can pass through the pinhole. The light was then collimated and divided by the beam splitter (NT45-008, Edmund Optics). One beam was directly detected by PMT2 (H10720-110, Hamamatsu), while the optical filter selectively attenuated the other beam according to the wavelength before being detected by

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PMT1 (H10720-110, Hamamatsu). The ratio of the two PMTs was then used to calculate the height of the objective.

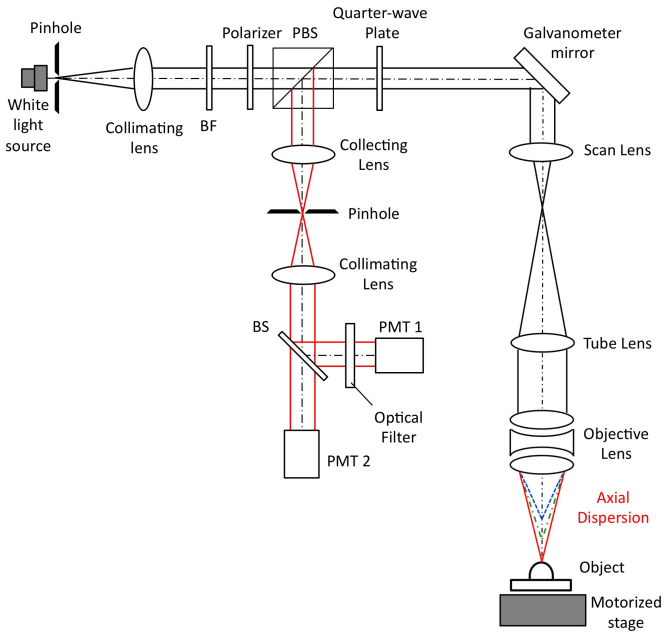

Fig. 3. A schematic diagram of the chromatic confocal microscope with the transmittance detection method. BF: bandpass filter, BS: beam splitter, PBS: polarizing beam splitter, PMT: photo multiplier tube.

3.2. Source

The chromatic confocal microscope uses broadband white light sources, such as superluminescent diodes, supercontinuum lasers, and Halogen and Xenon lamps. In this experiment, we used a Xenon lamp (PE300B-10F, Perkin Elmer Optoelectronics, Fremont, CA, USA) that is relatively inexpensive and has uniform illumination in the visible range. We measured the spectrum of the Xenon lamp using a spectrometer as shown in Fig. 4. Since the intensity peak in the source can affect CCM performance, we selected the wavelength range from 500 to 600 nm using a band pass filter where the illumination is uniform. In general, a shorter wavelength is advantageous in surface profiling since the lateral resolution is proportional to the wavelength due to the diffraction limit.

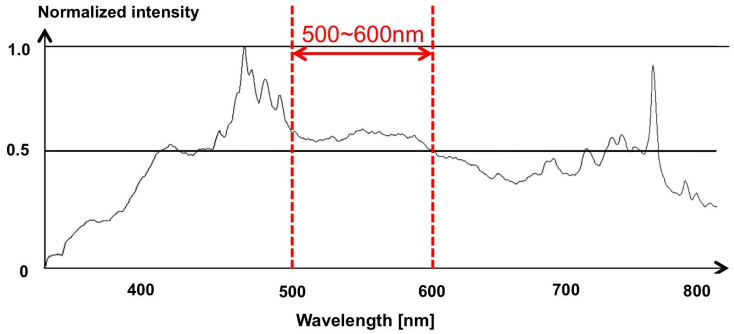

Fig. 4. Measured spectrum of the Xenon lamp.

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3.3. Optical filter

In this study, we proposed a novel method of detecting a peak wavelength for CCM using an optical filter. The optical filter should have a one-to-one relationship between the wavelength and transmittance. Especially, the optical filter with a linear transmittance according to wavelengths with large variation is ideal in the wavelength range of 500 to 600 nm. We selected a colored glass filter (BG7, Schott, Germany) for this study. Figure 5 shows an internal transmittance curve of the colored glass filter generated from the datasheet. Since the transmittance is almost a linear function of the wavelength, we can calculate the height of a specimen with a constant depth-sensitivity from the measured transmittance of the optical filter.

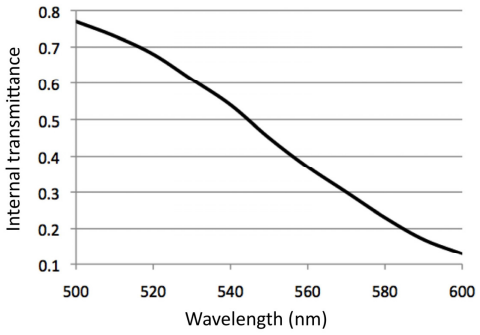

Fig. 5. Transmittance curve of the colored glass filter.

3.4. Lens design

Axial chromatic aberration can be induced by either refractive or diffractive optics [16, 19]. In this experiment, refractive optics utilizing the dispersion of glass material was used to induce the axial chromatic aberration. The scan lens, the tube lens and the objective lens were designed using multiple spherical lenses. All optics were designed using Zemax software to maximize surface profiling performance, i.e. maximizing depth detection range and field of view while minimizing the aberration under the diffraction limit.

The final optics design is shown in Fig. 6. The total optics length was 457 mm and the number of elements was 12. The numerical aperture and the effective focal length of the objective lens were 0.27 and 30.05 mm at the central wavelength of 550 nm, respectively. The chromatic focal shift that defines the depth detection range in the chromatic confocal microscope was calculated as 104.75 μm within the wavelength range of 500 to 600 nm as shown in Fig. 7. The chromatic focal shift was almost linear according to the wavelength, meaning we could easily convert the detected wavelength into the height of a sample. The optics had a diffraction-limited performance over the full field of 506 x 506 μm.

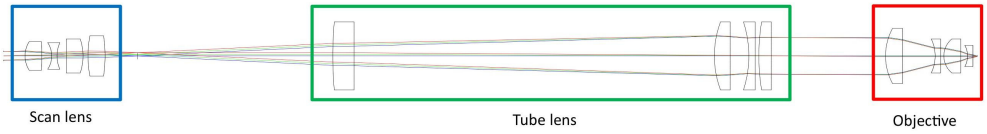

Fig. 6. Layout of the designed lens system.

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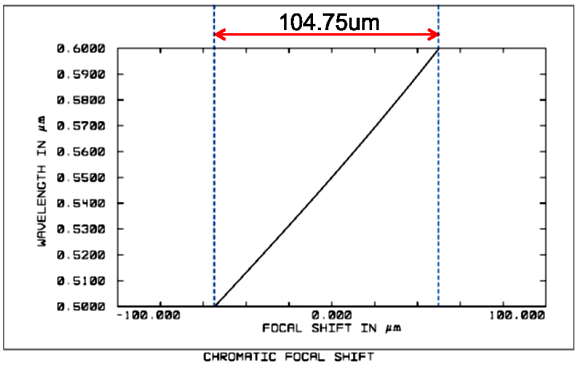

Fig. 7. Chromatic focal shift of the lens system.

4. Experiments

We verified performance of the system, including depth detection range, axial resolution, and lateral resolution by experimentation. We also acquired the 3D reconstruction of a certified standard specimen.

4.1 System performance

First, to assess the depth detection range and the axial resolution of the developed chromatic confocal microscope, we measured transmittance of the reflected light while moving a sample along the axial direction via a piezoelectric stage (MIPOS 500 SG, piezosystemjena Inc.). The system was calibrated using the relationship between the axial position and the transmittance. A scatter plot of the experimental data for depth and transmittance is shown in Fig. 8. The depth detection range, where the relationship between the transmittance and the depth is relatively linear, was measured as 108 μm. Since the relationship was not completely linear, we used a least-squares curve fitting using a fifth-degree polynomial. We then generated a lookup table from the curve fitting to measure the depth of the specimen from the transmittance of the reflected light. Using the calibrated lookup table, we were able to measure the depth without serious nonlinear error. The axial resolution of the chromatic confocal microscope is defined as the standard deviation of the measured depths on a stationary specimen [18]. In this experiment, the standard deviation or the axial resolution was measured as 1.54 μm at the central region. Transmittance curve slope as well as detector signal-to-noise ratio affects the axial resolution. This suggests that the axial resolution will be slightly different over the measurement range, due to the degradation of the detector signal at one end of the range with lower transmittance and the nonlinearity of the transmittance-depth relationship. We can improve the axial resolution of CCM by using higher NA objective lens at the expense of measurement range. Also, averaging will improve the signal-to-noise ratio, thus enhancing the axial sensitivity while reducing the detection speed. Thus, we should compromise between axial resolution, measurement range, and measurement speed depending on applications.

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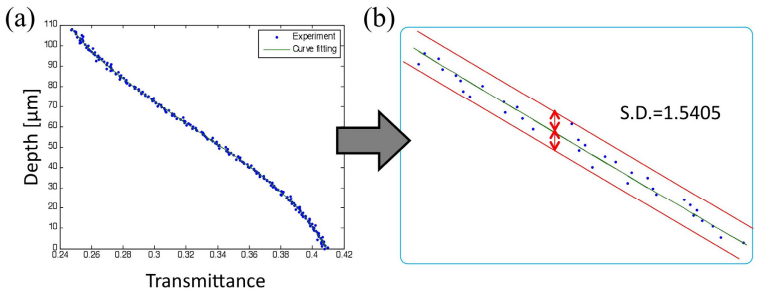

Fig. 8. Relationship between the depth of the sample and transmittance of the reflected light. (a) Scatter plot and curve fitting of the experimental data and (b) expanded view with the standard deviation (SD).

The lateral resolution of the system can be determined by the line-spread function (LSF), which is a derivative of the edge response function. The lateral resolution of the imaging system is defined as the full width at half maximum (FWHM) of the LSF [20]. Resolution of the chromatic confocal microscope is variable according to the wavelength (i.e. the height). In this experiment, we measured the representative lateral resolution using a He-Ne laser with a wavelength of 543 nm, which is approximately the center of the wavelength range. Figure 9(a) shows the edge image measured by the developed chromatic confocal microscope and the edge response function calculated from the edge image is shown in Fig. 9(b). By calculating the derivatives of the edge response function, we obtained the LSF and were able to measure the lateral resolution, or the FWHM of the system, which was found to be 0.98 μm.

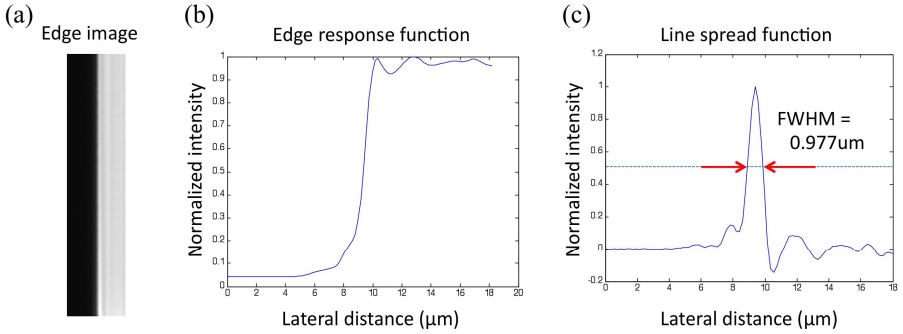

Fig. 9. Lateral resolution of the developed system.

4.2 Sample measurement

We measured the surface profile of a sample with a step height using the developed chromatic confocal microscope and the proposed transmittance detection method. The Korean Research Institute of Standards and Science certified the height of the sample as 11.355 ± 0.086 μm. The shape of the sample is shown in Fig. 10(a). We measured the 3D shape of the sample without axial scanning. Transmittance of the returning light was measured at each lateral position, while scanning the beam in the lateral direction only. The transmittance was then converted into the height using the lookup table. The rendered 3D surface profile is shown in Fig. 10(b). We clearly observed the pattern with the depth information. In order to analyze the depth measurement performance of the developed chromatic confocal microscope, we measured the cross-sectional profiles of the sample as shown in Fig. 10(c). The measured step height was 10.551 μm. Error between the measured height and the certified height was approximately 0.8 μm, which is smaller than the axial resolution of the developed system.

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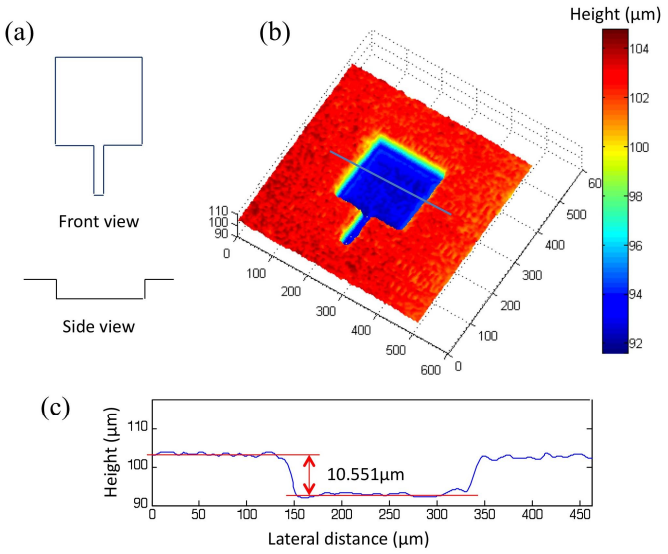

Fig. 10. Lateral resolution of the developed system.

5. Conclusion

We developed a chromatic confocal microscope with a novel wavelength detection method using transmittance. Using the proposed transmittance detection method, the peak wavelength of the reflected light, which contains depth information of the sample, can be instantaneously measured from the colored glass filter transmittance. Thus, the system is able to acquire the 3D surface shape of a sample without axial mechanical translation. With the optimally-designed and manufactured refractive lens system, a depth detection range of 108 μm, an axial resolution of 1.54 μm, and a lateral resolution of 0.98 μm was achieved. We successfully demonstrated 3D surface profiling of a standard sample with a step height. The height measurement speed of the proposed method is limited by the speed of the PMTs, which can be as fast as a few hundred Megahertz. This suggests that with a fast lateral scanning mechanism, such as a resonant galvanometer mirror, real-time 3D surface profiling can be achieved with micrometer resolution. This novel high-speed surface profiling method may be useful in many industrial applications, such as the real-time inspection of semiconductor and flat panel display manufacturing processes.

Acknowledgments

This work was supported by WCU (World Class University) program (R31-2008-000-10045-0) and Basic research program (2012R1A1A1041203) through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology.

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