Keynote speech

Twenty Years of R&D on Optical Interferometry for Industrial Applications

Katsuichi KITAGAWA

Twenty years have passed since we began to develop techniques of optical interferometry. This paper introduces some examples of our developments: 1) speed improvement by sub-Nyquist sampling, 2) profiling of a transparent film, 3) single-shot interferometry, and 4) film thickness profiling by interference color analysis.

1. Introduction

I will look back on the 20 years since I was involved in interferometric measurement technology development, and introduce the technologies that I have developed.

2. Encounter with interferometry and start of technology development

I first encountered optical interferometry in 1986. At that time, while investigating the technique for measuring the fine surface profile of polyester film, I discovered optical interferometry using the phase shifting method, and was deeply impressed by the skill and practicality of its principle. This led to a long relationship with WYKO, USA and Professor Wyant of the University of Arizona. Then, in 1993, while I was promoting the semiconductor inspection equipment business, I developed and commercialized an automatic magnetic head flatness measuring system using an optical profiler [1].

3. High-speed vertical scanning method (SB method)

At that time, when trying to apply optical interferometry to FA applications, the biggest problem was the slow measurement speed. To solve this problem, we started collaborative research with Ogawa Lab., Department of Computational Engineering, Tokyo Institute of Technology (TIT), and in 2000, developed a high-speed measurement algorithm named SB method [2]. This technology uses waveform restoration by the band-pass sampling theorem, and it has been commercialized as the surface profiler SP-500 [3], increasing the measurement speed up to that time by about ten times. In addition to being awarded the Technology Award of the Society of Instrument and Control Engineers (SICE), it was also featured on NHK TV "Close-up Gendai" as an example of the TLO's activities in TIT.

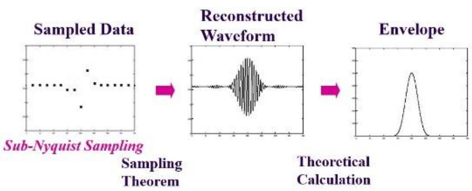


Fig. 1 Principle of SB method

4. Transparent film compatible

4.1 Substrate film measurement (KF method and NF method)

After that, in response to the needs of the semiconductor and LCD industries, we worked on the development of transparent film measurement technology, developed algorithms for thick film in 2002 and thin film in 2006, and commercialized the industry's first transparent film profiler.

When the film thickness of the transparent film is thicker than the coherent length, as shown in Fig. 2, there are two peaks in the interferogram: front reflection and back reflection. The two peaks are separated by a discriminant analysis method, and the surface height, backside height, and film thickness are determined from the detected peak positions (KF method) [4][5]. The lower limit of measurable film thickness is about 1 μm in optical film thickness. When the thickness of the transparent film is thinner than the coherent length, two peaks overlap as shown in Fig. 2, and it is difficult to separate the peaks by the KF method. I have developed a thin film measurement algorithm (NF method) based on a physical model [5]. As a result, it became possible to measure a 100 nm thin film of Si oxide (Fig. 3).

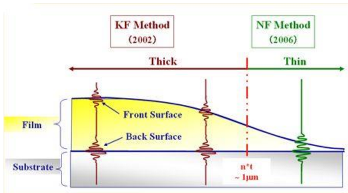


Fig. 2 Interferogram of transparent film and measurement algorithm

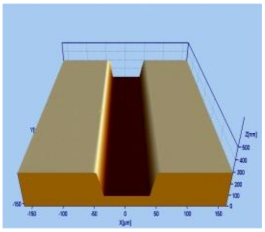


Fig. 3 Measured thickness profile of thin film (300/100nm) by NF method

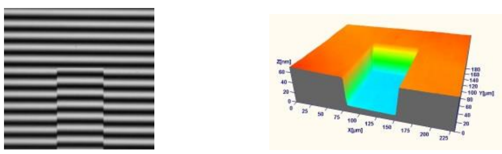
4.2 Independent film measurement (TF method) [6]

If the measurement target is an independent transparent film, it is possible to measure the film thickness by transmission interferometry, and we have proposed a method (TF method) that uses a commercially available surface profiler. The separately prepared flat surface is used as the measurement reference surface, the transparent film to be measured is inserted in the measurement optical path of the interference system, and the film thickness is determined from the change in the measured height of the reference surface. Stable measurement can be performed without being affected by the position of the film or waviness.

5. Single-shot measurement

5.1 Local model fitting method (LMF method) [7]

For the purpose of speeding up measurement and improving vibration resistance, we set up single-shot interferometry as a joint research theme with TIT in 2005 and worked on the development of a new algorithm for interference images. As a result, we developed a local model fitting method (LMF) that solves the problems of the conventional Fourier transform method. In this method, the fringe model function is adapted to the local intensity data to obtain the phase, and various methods have been devised to speed up the computation and enhance its practicality. Figure 4 shows the measurement result for the standard step of 50 nm, and the steep step profile can be measured without significant blurring.



(a) Interferogram (b) Measurement result

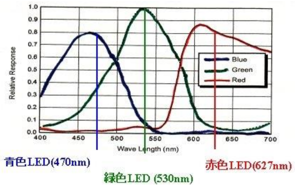
Fig. 4 Measurement of 50nm step by LMF method

5.2 Multi-wavelength single-shot interferometry [8]

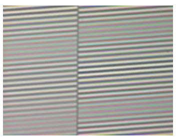
In order to expand the applications of the single-shot method, it is essential to expand the measurement range, that is, solve the problem of height difference limit between adjacent pixels. Therefore, we started research on multi-wavelength. For the multi-wavelength single-shot method, it is necessary to capture interference images of multiple wavelengths at the same time. From a cost standpoint, we want to avoid complicated optical systems. Therefore, we considered using a commercially available color camera. For simultaneous illumination of multiple wavelengths, the commercial RGB-LED lighting device in Fig. 5(a) was used. Figure 5(b) shows the spectral sensitivity characteristics of a color camera and the peak wavelengths of the three LEDs. With this imaging system, an image of 470 nm from the B frame, an image of 530 nm from the G frame, and an image of 627 nm from the R frame of the camera can be obtained. Later, we developed an illumination system using a multi-wavelength band-pass filter, and realized downsizing of the device and improvement of versatility. In order to obtain the height from the color image, we have developed (1) crosstalk compensation method [9]; (2) fringe frequency estimation method [10]; (3) wavelength unwrapping method [11].

Furthermore, in order to further expand the measurement range, three wavelengths were optimized, and as shown in Fig. 5(c)(d), it became possible to measure a step of 8μm [12]. Using this technology, we have developed an automatic film thickness measurement system for inkjet color filters (IJCF) [Fig. 5(e)(f)] [8]. This technology was commercialized as the three-wavelength single-shot surface profiler MW-500 [3]. We received the Technology Award of the Japan Society for Precision Engineering (JSPE).

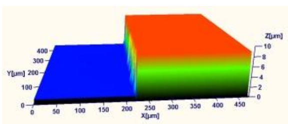
(a) RGB LEDs



(b) Illumination wavelengths and spectral sensitivity of camera

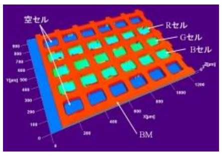


(c) Interferogram of 8μm step



(d) Measured 8μm step

(e) Automatic IJCF thickness measurement system



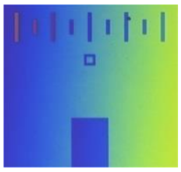
(f) Measured IJCF surface

Fig. 5 Three wavelength single-shot interferometry

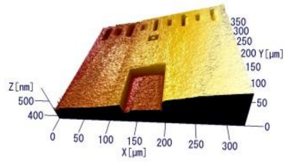
6. Measurement by interference color analysis

6.1 Height measurement

In order to solve the horizontal resolution degradation problem of the carrier fringe introduction method, we searched for a method that does not require the introduction of carrier fringes and developed a measurement method by interference color analysis (Global Model Fitting method; GMF) [12]. The interference signal model is least-squares-fitted to the RGB intensity values of multiple points obtained from the interference image of three wavelengths, and the surface height and model parameters are simultaneously obtained. The measurement results of the 50 nm step are shown in Figs. 6(a) and 6(b). This technology was also featured in the SPIE Newsroom [13].



(a) Color image

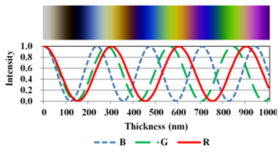


(b) Measured surface profile

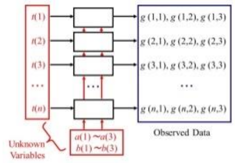
Fig. 6 Measurement of 50nm step by GMF method

6.2 Film thickness measurement

The GMF method described in the previous section can be used to measure the thickness of transparent films. That is, thin-film interference colors seen in oil films or soap films are imaged under three-wavelength illumination, and the film thickness at each point and model parameters are estimated simultaneously (GMFT method) [14, 15]. The measurement principle is shown in Fig. 7(a)(b). In addition, the measurement results of a vertically flowing soap film are shown in Fig. 8(a)(b).

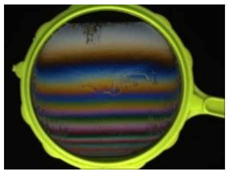


(a) Color chart and RGB signals

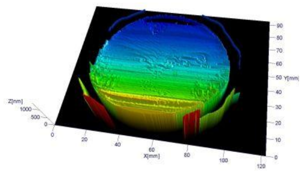


(b) Measurement principle

Fig. 7 Film thickness measurement by interference color analysis (GMFT)



(a) Color image



(b) Measured film thickness

Fig. 8 Measurement of flowing soap film by GMFT method

7. Conclusion

Due to recent dramatic improvements in electronics technology and computer's ability, more advanced algorithms have been put to practical use in shape measurement by optical interferometry, and remarkable results have been obtained. Further technological development is expected in the future.

Acknowledgment: These technical developments were carried out while I was working for Toray Industries, Inc. and Toray Engineering Co., Ltd. I have received the support and cooperation of many people, including members of the Hidemitsu Ogawa & Masashi Sugiyama Laboratory of TIT, the formerly Optical Engineering Laboratory of Riken, and the Mechano-photonics Technical Committee (JSPE). I would like to express my deep gratitude here.

References

[1] Osamu Takahashi, Susumu Matsumoto, Tsuyoshi Kobayashi, Nobuyuki Yoshida and Katsuichi Kitagawa.: Automatic ABS inspection system of magnetic heads by image processing technology, Proc. of SICE Annual Conference, 421 (1994) (in Japanese)

[2] Akira Hirabayashi, Hidemitsu Ogawa, Tatsuya Mizutani, Ken Nagai and Katsuichi Kitagawa: Fast Surface Profiling by White-Light Interferometry Using a Sampling Theorem for Band-Pass Signals, Transactions of SICE, **36**, 16 (2000) (in Japanese)

[3] http://www.scn.tv/user/torayins/ (Toray Inspection System Home Page) (visited in 2014)

[4] K. Kitagawa: Simultaneous measurement of film surface topography and thickness variation using white-light interferometry, Proc. of SPIE, **637507** (2006)

[5] K. Kitagawa: Chapter 29 Film surface and thickness profilometry, in "Handbook of Optical Metrology -Principles and Applications-", Edited by Toru Yoshizawa, CRC Press, 677 (2009)

[6] K. Kitagawa: Thin film thickness profile measurement using an interferometric surface profiler, Proc. of SPIE, **671607** (2007)

[7] M. Sugiyama, H. Ogawa, K. Kitagawa, and K. Suzuki: Single-shot surface profiling by local model fitting, Appl. Opt. **45**, 7999 (2006)

[8] Katsuichi Kitagawa, Hiroki Sugihara, Tatsuhiko Tsuboi, Kazuyoshi Suzuki and Masafumi Otsuki: Automatic Film Thickness Measurement System for Inkjet-Based Color Filters Based on Three-Wavelength Single-Shot Interferometry, J. Jpn. Soc. Precis. Eng., **78**, 112（2012） (in Japanese)

[9] Katsuichi Kitagawa: Crosstalk Compensation for Three-Wavelength Interferometry, SICE Trans. on Industrial Application, **8**, 113 (2009) (in Japanese)

[10] Katsuichi Kitagawa: Two-Dimensional Frequency Estimation for Fringe Analysis by Phase Gradient Detection, SICE Trans. on Industrial Application, **8**, 108 (2009) (in Japanese)

[11] Katsuichi Kitagawa: Optimum Wavelength Selection to Extend the Unambiguous Measurement Range of the Three-wavelength Single-shot Interferometry, Transactions of SICE, **50** (4), (2014) [to be printed] (in Japanese)

[12] K. Kitagawa: Single-shot surface profiling by multiwavelength interferometry without carrier fringe introduction, J. Electron. Imaging, **21**, 021107 (2012)

[13] K. Kitagawa: Single-shot interferometry without carrier fringe introduction, SPIE Newsroom (August 21, 2012). http://spie.org/x88848.xml. DOI: 10.1117/2.1201207.004360.

[14] K. Kitagawa: Thin-film thickness profile measurement by three wavelength interference color analysis, Appl. Opt., **52**, 1998 (2013)

[15] Katsuichi Kitagawa and Masafumi Otsuki: "Wide-view Transparent Film Thickness Measurement System by Interference Color Analysis", J. Jpn. Soc. Precis. Eng., **79**, 1078 (2013) (in Japanese)

This is an English translation of the paper:
Katsuichi Kitagawa: [Keynote speech] "Twenty Years of R&D on Optical Interferometry for Industrial Applications", Proc. of JSPE Spring Meeting (Tokyo, March 2014).
(original in Japanese; translated by the author)