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2016

Lee, C.-Y., Hyun, S.-W., Kim, Y.-J., & Kim, S.-W. (2016). Optical inspection of smartphone camera modules by near-infrared low-coherence interferometry. *Optical Engineering*, 55(9), 091404-.

<https://hdl.handle.net/10356/87274>

<https://doi.org/10.1117/1.OE.55.9.091404>

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Optical inspection of smartphone camera modules by near-infrared low-coherence interferometry

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Abstract. High-resolution cameras used for smartphones are comprised of multiple aspheric lenses, a spectral filter, and a semiconductor image sensor, which are packaged together into a single module with tight geometrical tolerances. We investigated the technical possibility of near-infrared low-coherence interferometry for non-destructive geometrical inspection of the complex camera module to examine the inside packaging state. This tomographic scheme enabled us to measure the relative axial position of each inside component and also the lateral surface profile of the image sensor, allowing for comprehensive three-dimensional quality assurance of the whole camera module during the packaging process. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.55.9.091404]

Keywords: low-coherence interferometry; camera module; nondestructive inspection.

Paper 151832SS received Dec. 28, 2015; accepted for publication Feb. 22, 2016; published online Mar. 14, 2016.

1 Introduction

High-resolution cameras used for smartphones or tablet PCs are configured with multiple aspheric lenses designed to attain not only a large field-of-view in the image plane, but also a wide view angle in the object space.^{1–3} All the lenses are securely packaged into a tiny single module and then integrated with additional components such as spectral filters and image sensors. Accordingly, during the assembly process of such a camera module, it is important to ensure that the alignment accuracy and rigidity among all the components are fulfilled as required for the final intended image quality. As a nondestructive means of postassembly dimensional inspection, x-ray tomography is available, but its state-of-the-art measurement resolution is not precise enough to satisfy today's inspection requirements.⁴ In addition, destructive examination is not an option either because it permits only sampling inspection and often alters the original internal state during the breakaway process.

In this paper, an optical tomographic method is presented which allows for viewing the inside state of camera modules for nondestructive inspection. This method utilizes a near-infrared (NIR) diode source of a wide spectral bandwidth to perform low-coherence optical interferometry,^{5–7} attempting to identify the relative axial location of each aspheric lens with micrometer-scale resolution. In addition, the three-dimensional (3-D) surface profile of the flat image sensor is reconstructed so that its warpage introduced during assembly is assessed with respect to the lens subassembly. This method is found fast and robust enough to be applicable for real-time geometrical inspection on site during mass-production of camera modules comprising many optical components within a tiny volume.

2 Measurement System Design

Figure 1 shows one of the camera modules selected as the measurement sample in this study. It comprised three major components: a lens subassembly, an IR filter, and a flat semiconductor image sensor. The lens subassembly has a 2.0-mm entrance aperture diameter, consisting of five pieces of aspheric lenses precisely fabricated to provide a wide view angle of $\pm 35^\circ$ and also a large 5.0-mm field-of-view in the image plane. The IR filter is inserted to cutoff the IR radiation of 700- to 1200-nm wavelengths, with high spectral transmittance for the visible light of 400- to 700-nm wavelengths. The image sensor provides 13 mega pixels (4028×3120) with a $1.12\text{-}\mu\text{m}$ spatial resolution in image capturing. All these internal components have to be assembled with tight geometrical tolerances so that the achievable imaging resolution of the camera module is not be degraded as a whole.

Figure 2 shows the optical configuration of the low-coherence scanning interferometer built in this study. The interferometer is basically of the Twyman–Green type to implement low-coherence interference between the measurement and reference arms. The camera module put to test is placed stationary in line with the optical axis of the measurement arm. The reference mirror is translated over a 9-mm scanning distance with an incremental 30-nm step using a piezoelectric linear stage. Two distinct illumination schemes are adopted: one is the collimated illumination shown in Fig. 2(a) used for sequential detection of the axial position of each component surface, and the other is the diverging illumination of Fig. 2(b) for lateral surface profile measurement of the image sensor.

The light source selected is a superluminescent diode (SLD) of a $\sim 1.0\text{-mW}$ average power with a 52-nm spectral

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Fig. 1 A camera module selected as the target sample: (a) a breakaway view and (b) ray tracing for geometrical optics design analysis.

Fig. 2 Optical layouts of scanning low-coherence interferometry for nondestructive inspection of the camera module: (a) collimated illumination for axial position measurement and (b) diverging illumination for surface profile measurement.

bandwidth centered at a 1552.6-nm wavelength as in the optical spectrum shown in Fig. 3. The NIR source light was selected as it is able to penetrate into all the lens surfaces, front or rear, which are antireflective coated for visible light as illustrated in Fig. 3(a). At the same time, about 4% of

NIR light is reflected from every lens surface to create interference with the reference beam. In addition, the NIR source light spectrum lies outside the cut-out spectral range (700 to 1200 nm) of the IR spectral filter, so it can reach the image sensor located at the bottom of the camera module. The

Fig. 3 Light source selection: (a) transmittance of each inside component of the camera module and (b) measured spectrum of the NIR SLD light source with an optical spectrum analyzer.

resulting interference signal is captured using an IR CCD camera of 320×256 pixels made of InGaAs PIN photodiodes (OWL SW1.7, Raptor-photonics), offering high sensitivity in the 0.9- to 1.7- μm wavelength range. The image capturing was performed at a sampling rate of 349 frames/s.

3 Measurement Results and Discussion

3.1 Axial Position Measurement

Figure 4(a) shows an interference signal actually measured during the detection process of the axial positions of the internal components using the collimated illumination of Fig. 2(a). The measured interference signal comprised many peaks since each internal component has two surfaces, i.e., front and rear, reflecting light separately. There were also seen myriad small peaks attributable to multiple reflections between adjacent surfaces. With prior knowledge on the thickness and position of each component together with its refractive index, spurious peaks due to multiple reflections were ignored by trial and error. True peaks were identified with their corresponding component surfaces abbreviated as S1: front surface, S2: rear surface, W: window glass, L#: the #th lens, and F: the IR filter. For example, L1S1 indicates the front surface of the first lens from the top of the camera module. Figure 4(b) shows a magnified view of the peak interferograms obtained for L2S1 and L1S2, in which the 1552.6-nm carrier fringe signal of the NIR light source was clearly seen. The axial location of

Table 1 Measured distances between two neighboring surfaces within the camera module.

Surfaces	Measured distance (μm)
WS1 to WS2	614.5 ± 3.0
WS2 to L1S1	443.0 ± 1.7
L1S1 to L1S2	1278.6 ± 4.4
L1S2 to L2S1	90.9 ± 0.2
L2S1 to L2S2	496 ± 0.8
L2S2 to L3S1	383.3 ± 1.3
L3S1 to L3S2	759.3 ± 2.5
L3S2 to L4S1	366.7 ± 8.3
L4S1 to L4S2	690.2 ± 10.3
L4S2 to L5S1	101.9 ± 6.0
L5S1 to L5S2	1347.9 ± 11.8
L5S2 to FS1	659.4 ± 12.6
FS1 to FS2	461.4 ± 1.8
FS2 to sensor	325.7 ± 3.9

Fig. 4 Axial position measurement: (a) interference signal monitored at the center CCD pixel during scanning along the full depth of the camera module, (b) enlarged interferograms of the first lens and second lens peaks, and (c) repeatability for the distance between the first lens and second lens over 21 consecutive measurements.

each peak was determined precisely by adopting the centroid algorithm^{8,9} with processing of all the intensity data sampled with a 30-nm scanning step. The measured peak position displayed a repeatability of 0.2 μm , as demonstrated from

21 consecutive measurements given in Fig. 4(c). The relative distance between L2S1 and L1S2, for which the design value was 90.0 μm , was estimated to be 90.9 μm . The low-coherence interferometric test performed in this study enabled us

Fig. 5 Measured surface profile of the image sensor: (a) reconstructed 2-D height map before compensation, (b) sectional profile of the line A-A', and (c) magnified views of the sections I and II marked in (b). Error bars indicate the standard deviation of each pixel point over 19 consecutive samplings. (d) Repeated measurement results at section III marked in (c).

to successfully quantify the distances between all the internal components with micrometer resolutions as presented in Table 1.

3.2 Surface Profile Measurement

The lateral surface profile of the image sensor located at the bottom of the camera module was also measured using the diverging illumination of Fig. 2(b). In comparison to the collimated illumination case of Fig. 2(a), the diverging illumination was achieved by inserting a focusing lens (FL) between the beam splitter and the specimen. The focal point of the inserted FL was aligned to coincide with the effective focal length of the specimen camera module. For this, the two-dimensional (2-D) interference pattern between the reference flat mirror and the image sensor plane was captured using the whole pixels of the IR camera while the needed phase shifting was induced by a preassigned 70-deg phase shift consecutively by moving the reference mirror along the optical axis. Then a total of 10 phase-shifted interference patterns were taken and processed with the A-bucket algorithm,^{10,11} which allowed for accurate elimination of any phase-shift errors by iterative least-squares fitting. The sensor surface profile was finally reconstructed by phase unwrapping as shown in Fig. 5(a). The NIR source light experienced various aberrations during propagation through the lens assembly, because all the internal lenses have been designed to work for image forming using only visible light. Thus, the measured surface profile yielded a significant distortion as depicted with a blue line profile in Fig. 5(b). The distortion was compensated by putting a flat gold mirror on the image sensor plane within the camera module. The red line profile in Fig. 5(b) shows the compensated sensor profile by subtracting the distortion value obtained by measuring the flat gold mirror instead of the image sensor. The finally measured sensor area corresponded to a 1-mm diameter, with a maximum height variation of $\sim 0.93 \mu\text{m}$ in peak to valley. The measurement repeatability was estimated to be 8 nm from 19 consecutive measurements as shown in Figs. 5(c) and 5(d).

3.3 Warpage Measurement

The image sensor used in the camera module was fabricated on a thin silicon substrate, being vulnerable to surface bending even for small mechanical forces exerted in the process of packaging with other internal components. The surface bending tends to significantly deteriorate the image quality and resolving power of the image sensor,^{12,13} therefore it needs to be quantified in terms of the warpage for quality assurance as specified in Fig. 6(a). The measured warpage was 735 nm with a concave-type bending as depicted in Fig. 6(b), which was then extrapolated to $5.4 \mu\text{m}$ over the entire image sensor plane of a 7.32-mm diagonal length.

4 Conclusions

Our method of low-coherence scanning interferometry using a SLD light source enabled us to perform nondestructive geometrical inspection of a camera module comprised multiple internal components: five pieces of aspheric lenses, an IR cutoff filter, and an image sensor. The SLD source was selected to offer a wide spectral bandwidth of 52 nm at a 1552.6-nm center wavelength, allowing for effective

Fig. 6 Warpage measurement for the image sensor surface within a 1-mm field-of-view: (a) warpage definition using five point heights and (b) measured diagonal line profiles.

generation of well-localized interferograms from the internal lens surfaces of visible light antireflective coating. The method enabled us to measure the relative position of each internal component with micrometer precision. In addition, the 3-D surface profile of the image sensor was measured for warpage evaluation with nanometer precision. The proposed method is expected to be utilized for nondestructive fail/pass inspection of the camera module during packaging.

Acknowledgments

This work was supported by the National Research Foundation of the Republic of Korea (NRF-2012R1A3A1050386) and the Scholar Program by the Samsung Electro-Mechanics Co. Ltd. S. Hyun was partly supported by the Korea Basic Science Institute Grant (D35500).

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