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Harnessing spectral property of dual wavelength white LED to improve vertical scanning interferometry

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Unlike a conventional white light source that emits a continuous and broad spectrum of light, the dual wavelength white light emitting diode (LED) generates white light by mixing blue and yellow lights, so there are two distinct peaks in its intensity spectrum. Prior works had shown that the spectral property of the dual wavelength white LED can affect the vertical scanning interferometry negatively if the spectral effects are not compensated. In this paper, we shall examine this issue by modeling the spectral property and variation of the dual wavelength white LED, followed by investigating its effects on the interference signal of vertical scanning interferometry. Instead of compensating the spectral effects of the dual wavelength white LED, we harness its spectral property to improve the performance of a phase-based height reconstruction algorithm in vertical scanning interferometry. © 2013 Optical Society of America

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1. Introduction

Vertical scanning interferometry is an established optical method for surface height profile measurement. It is done by analyzing a series of interference patterns of low coherence light with known optical path differences (OPDs) among them. As white light is commonly used as a low coherence light source, the vertical scanning interferometry is also known as white light interferometry or coherence scanning interferometry.

Except for the light source, there is no major change in the hardware of vertical scanning interferometry in the past two decades. Driven by recent advancement in lighting technology and new applications such as dynamic characterization of micro-electro-mechanical systems (MEMS), modern

and hybrid light sources such as supercontinuum light source [1–3], phosphor-based white LED [4], nonphosphor white LED [5], a combination of two low coherence light source [6], etc., have been used as the light source in vertical scanning interferometry. Among these, the high power white LED is the most commonly used solution due to its advantages in modulation frequency, brightness, affordability, and availability.

There are three types of commercial off-the-shelf white LEDs: red–green–blue (RGB) white LED, phosphor-based and nonphosphor (which is also known as phosphor-free) white LEDs. Among these three types, RGB white LED is primarily used for display device, and phosphor-based and nonphosphor white LEDs are primarily used for illumination purpose [7]. While RGB white LED generates white light by mixing the three primary colors, phosphor-based and nonphosphor white LEDs generate white light by mixing blue and yellow lights. In

terms of spectral property, phosphor-based and nonphosphor white LEDs are similar: there are two distinct peaks in the intensity spectrum. The difference between them is in the mechanism of light generation. So both phosphor-based and nonphosphor white LEDs are considered as the dual wavelength white LEDs with two distinct peaks in the intensity spectrum.

In this paper, we model the spectral property and variation of the dual wavelength white LED, followed by investigating its effects on the interference signal of vertical scanning interferometry. By doing so, we can exploit the spectral property of the dual wavelength white LED to improve the performance of a phase-based height reconstruction algorithm in vertical scanning interferometry.

2. Physical Model of Interferometry

In vertical scanning interferometry (as shown in Fig. 1), the light beam from the light source is split into two: one to the reference surface and the other to the measurement surface, then these light beams are reflected and interfered with each other. An interference pattern occurs when the between these two light beams is small, within the coherence length of the light source. The interference pattern is known as interferogram, and is recorded by area-based photo-sensitive sensor such as charge-coupled device (CCD) camera. A correlogram is the function of intensity response of each pixel against the OPD, and its envelope function is known as fringe contrast function. The correlogram is the raw data being stored and further processed for height profile measurements, and it can be represented as followed:

$$I_{\text{interference}}(z) = C_1 \int_{\text{bandwidth}} \int_0^{\theta_0} \{k^2 \times \cos[2k(z - z_0) \times \cos \theta + \phi] \times \sin \theta \cos \theta d\theta\} F(k) dk, \quad (1)$$

where C_1 is a constant, z is an independent variable that corresponds to height change, z_0 is the height that corresponds to the surface profile, k is the angular wave number ($k = 2\pi/\lambda$), $\sin \theta_0$ is the numerical

Fig. 1. Schematic diagram of vertical scanning interferometry

aperture (NA) of objective lens, ϕ is the phase offset, and $F(k)$ is the intensity spectrum of the light source.

The details on the derivation and modeling of the intensity response can be found in Kino and Chim [8,9] and de Groot and de Lega [10].

The intensity spectrum of the light source affects the contribution of individual wavelengths to the interference signal. In the following sections, we shall investigate the spectral effects of the dual wavelength white LED in vertical scanning interferometry.

3. Dual Wavelength White LED

Besides optical and electrical power, commercially off-the-shelf white LED is categorized according to its correlated color temperature (CCT). CCT is the temperature with which the perceived color of black body radiator best approximates, however, it is meaningful only if the light source is nearly white [11]. An example application of CCT for interior illumination: warmer white light (lower CCT) is used in homes to promote relaxation while cooler white light (higher CCT) is used in offices to enhance concentration [12].

While the desired CCT is achieved by varying the intensity spectrum of the dual wavelength white LED in a designed and controlled manner, the manufacturing process also introduces some undesired variation to the intensity spectrum. The spectral variation of white LED is an issue that warrants the U.S.-based National Electrical Manufacturers Association (NEMA) to publish SSL 3-2010 "High-Power White LED Binning for General Illumination" to manage it [13,14].

Other than the designed and the undesired spectral variations mentioned above, the intensity spectrum of the dual wavelength white LED can vary depending on its operating condition [5,15] and optical degradation [16,17]. For example, (1) when the white LED is being pulsed at high frequency, the relative intensity of the blue and yellow light components changes [5], and (2) the center wavelength of blue light shifts by 7 nm when the duty cycle in pulsing mode is changed from 1% to 10% [15].

As the intensity spectrum of the dual wavelength white LED varies among LED manufacturers/models/batches, two assumptions are made to model the spectrum of the dual wavelength white LED and its spectral variation in this study:

Assumption (1): the intensity spectrum of the dual wavelength white LED has two Gaussian functions and it can be modeled as follows:

$$f(k) = BY \text{ ratio} \times e^{-\left(\frac{k-k_{\text{blue}}}{\sigma_{\text{blue}}}\right)^2} + e^{-\left(\frac{k-k_{\text{yellow}}}{\sigma_{\text{yellow}}}\right)^2}, \quad (2)$$

where k is the angular wavenumber ($= 2\pi/\lambda$), k_{blue} indicates the peak angular wavenumber of blue light, k_{yellow} indicates the peak angular wavenumber of yellow light, σ_{blue} indicates the spread of blue light in

Fig. 2. Graphical comparison of the intensity spectrum of simulated and commercially available phosphor-based white LED with different CCT of: (a) warm white, BY ratio = 0.59, (b) daylight white, BY ratio = 1.14, and (c) cool white, BY ratio = 1.6.

the spectral domain, and σ_{yellow} indicates the spread of yellow light in the spectral domain.

In general, the wavelengths of blue and yellow lights are 450 nm (13.96 rad/nm) and 570 nm (11.02 rad/nm), respectively, and the spread of blue and yellow lights in spectral domain are 0.4941 and 1.439 rad/nm. These values vary slightly among manufacturers/model.

Assumption (2): the spectral variation of white LED is the result of the variation in CCT and/or degradation [16,18,19]. These variations are represented in terms of the blue to yellow ratio [BY ratio in Eq. (2)]: when the BY ratio is approximately 1, the intensities of blue and yellow lights are approximately equal, and the white light is daylight white and the CCT is around 4000–5000 K; when the yellow light is stronger than blue light (BY ratio is less than 1), the white light become warmer and the CCT is around 2000–4000 K; when the blue light is stronger than yellow light (BY ratio is larger than 1), the white light become cooler and the CCT is around 5500–10,000 K.

These two assumptions are validated by comparing three commercially off-the-shelf phosphor-based white LEDs with different CCT to their simulated counterparts. Figure 2 shows that the simulated intensity spectrums are close to the commercially available products.

4. Effects on Correlogram

Researchers [4,5] have reported that the use of the dual wavelength white LED introduces a distinctive feature, which means that the fringe contrast function cannot be modeled as a single Gaussian function, and the distinctive feature may affect the measurement result negatively. Although it has been shown that the distinctive feature is the result of destructive interference between the blue and yellow lights of the dual wavelength white LED [20], the work has focused on the dual wavelength low coherence light source and has not further investigated the dual wavelength white LED in detail. Next, we shall investigate the effects of its spectral variation

to the interference signal of vertical scanning interferometry.

To do so, a collection of intensity spectrum with increasing BY ratio from 0.5 to 1.7 (from warm white light to cool white light) at a step increment of 0.1 is selected for study. For each BY ratio, the corresponding correlogram is simulated based on the generalized model as shown in Eq. (1).

Figure 3 shows that a distinctive feature exists regardless of the spectral variation of the dual wavelength white LED.

To quantify the effects of the spectral variation on the correlogram, the correlogram is further processed by applying a Gaussian-based low pass filter (refer to Appendix A for more detail) to extract the envelope of correlogram (also known as fringe contrast function), and then followed by applying the peak and valley detection algorithms. With the feature extraction process illustrated in Fig. 4, the distinctive feature (highlighted in Fig. 4) is transformed into two features: the valley and the peak. The positions of the peak and valley (x_{peak} and x_{valley} in Fig. 4) are measured with respect to the

Fig. 3. Effects of changing the blue to yellow ratio (BY ratio) of the dual wavelength white LED on correlogram. (Numerical aperture of objective is assumed to be 0.4.)

Fig. 4. Graphical illustration on how the distinctive feature due to the dual wavelength white LED is further processed and characterized by two features (highlighted in red), which were made out of x_{valley} , y_{valley} , x_{peak} , and y_{peak} .

global peak of the fringe contrast function (which is 0 in Fig. 4) while the amplitudes of the peak and valley (y_{peak} and y_{valley} in Fig. 4) are measured with respect to the constant signal (which is 0.5 in Fig. 4). These four variables are selected to quantify the effects of changing BY ratio on the correlogram, and the changes of these two features against the BY ratio are shown in Fig. 5.

Figure 5(a) shows that the position of the peak is independent of the BY ratio, and the amplitude of the peak increases with the BY ratio. On the other hand, Fig. 5(b) shows that the position of the valley decreases rapidly with the BY ratio for BY ratio ≤ 1 and decreases at a much slower rate for BY ratio > 1 . The amplitude of the valley is at the minimum when the BY ratio is approximately 1.2. These changes can be used to monitor/trace the undesired optical degradation of the dual wavelength white LED [16–18] in vertical scanning interferometry.

Fig. 5. Effects of changing BY ratio on correlogram: (a) the peak, (b) the valley as indicated in Fig. 4. (Numerical aperture of objective is assumed to be 0.4.)

The effects of the spectral variation on the correlogram in spatial frequency domain is shown in Fig. 6, and it is consistent with earlier observations: the corresponding correlogram consists of two high frequency components that correspond to the dual wavelength components in the light source, and the ratio between these two high frequency components is equivalent to the BY ratio.

This section shows that with the dual wavelength white LED, there are two high frequency components and the distinctive feature (highlighted in Fig. 3) in the correlogram of vertical scanning interferometry. The magnitude and position of the distinctive feature are subjected to the spectral variation of the dual wavelength white LED, and these changes can be used to monitor and trace the undesired degradation of the dual wavelength white LED [16–18] in vertical scanning interferometry.

5. Improved Height Reconstruction Algorithm

Surface height reconstruction algorithm can be categorized into two approaches: (1) fringe contrast-based approach and (2) phase-based approach. Fringe contrast based approach recovers the height information by finding the maximum of the fringe contrast function (which is the envelope of correlogram); while phase-based approach transforms the correlogram into frequency domain, followed by analyzing the phase information.

In general, the phase-based approach is superior to the fringe contrast based approach because (1) based on communication theory, the phase information is more robust to noise compared to the amplitude information, and (2) the phase-based approach makes use of the prior knowledge such as the wavelength of light source [21]. With these considerations, we have searched for a suitable reconstruction algorithm among those using the phase-based approach and identified the phase-crossing algorithm by Pawlowski *et al.* [21] as the reconstruction algorithm

Fig. 6. Effects of spectral variation of the dual wavelength white LED on correlogram expressed in spatial frequency.

in which its performance may be improved by the spectral property of the dual wavelength white LED.

The working principle of Pawlowski *et al.*'s phase-crossing algorithm [21,22] is that the location of zero (which corresponds to the height information) is the singular point at which the phase of the interference signal contributed by different wavelengths of light is equal to each other. In Pawlowski *et al.*'s phase-crossing algorithm, it is assumed that a conventional white light source which its spectrum has only one dominant wavelength is used and the correlogram can be represented as follows:

$$g(z) = a + b(z - z_0) \cos(2\bar{k}(z - z_0) + \alpha(\bar{k})), \quad (3)$$

where z is the defocus position, a is the DC component in the interference signal, b is the fringe contrast function, z_0 is the height of the sample surface, $\bar{k}$ is the mean wave number, and α is the phase difference between the reference and the sample arms.

Then the correlogram is decomposed into multiple (minimum of 2) interference signals contributed by different wavelengths of light. Lastly, the height information is recovered by finding the singular point at which the phase of all decomposed interference signals is equal. There are three major steps in the implementation of the phase crossing algorithm:

- Step (1): a region of the correlogram is selected based on the use of a local standard deviation estimator.
- Step (2): the selected region of the correlogram is Fourier transformed, and two filter windows are applied to extract the interference signals contributed by two narrow band signals.
- Step (3): the phase information of the extracted interference signals is recovered by Fourier transform method [23]. Last, the location where the extracted interference signals have equal phase (phase-crossing point) is determined.

For detailed implementation, please refer to Appendix B.

Figure 7 illustrates the implementation of the phase-crossing algorithm with the conventional

white light source. As the effective spectrum of the conventional white light has only one dominant wavelength, there is only one peak in the spatial frequency domain of the correlogram. To extract the interference signals contributed by different wavelengths of light, two filter windows (on the left and right of the only peak in the frequency domain) are applied. After extracting the two interference signals contributed by different wavelengths of light, the phase information of each interference signal is recovered and the phase-crossing point is determined. Based on its working principle, the quality of the extracted interference signals is critical to its performance.

Fig. 7. Illustration of the phase-crossing algorithm by Pawlowski *et al.* [21] with the conventional white light source: (a) a region of the correlogram is selected for further processing, (b) the selected region is Fourier transformed and two filter windows are applied to extract the interference signals contributed by two narrow band signals, and (c) the phase information of the extracted interference signals are recovered and the phase-crossing point is identified.

Based on the spectral properties of the dual wavelength white LED studied earlier, we propose that the use of the dual wavelength white LED can improve the quality of filtering/extracting of interference signal contributed by different wavelengths of light. That is, the phase-crossing algorithm may exploit the spectral properties of the dual wavelength white LED and improve its performance.

With the dual wavelength white LED, the correlogram is made out of two high frequency components that correspond to two peaks in its spatial frequency domain. With these two peaks in the spatial frequency domain, the filter windows can extract the interference signal contributed by different

Fig. 8. Illustration of the phase-crossing algorithm by Pawlowski *et al.* [21] with the phosphor-based white LED: (a) a region of the correlogram is selected for further processing, (b) the selected region is Fourier transformed and two filter windows are applied to extract the interference signals contributed by two narrow band signals, and (c) the phase information of the extracted interference signals is recovered and the phase-crossing point is identified.

wavelengths of light better. Figure 8 illustrates the implementation of the phase-crossing algorithm with the dual wavelength white LED. As the effective spectrum of the dual wavelength white LED has two dominant wavelengths, there are two peaks in the spatial frequency domain of the correlogram. With two distinct peaks in the spatial frequency domain, the interference signals contributed by different wavelengths of light can be separated and extracted better.

6. Experiment and Verification

First, simulation is used to evaluate the proposed improvement of the phase-crossing algorithm by the use of the dual wavelength white LED. Four sets of correlogram are simulated: one is based on the conventional white light source; another three sets are based on the dual wavelength white LEDs with the BY ratio of 0.59, 1.14, and 1.60. A line profile of 1 μm step height is selected; the line profile consists of 256 surface points and each surface point has a corresponding correlogram. The sampling interval of the correlogram is 50 nm, and each correlogram is corrupted by Gaussian white noise (zero mean, variance of 0.02). Figure 9 compares the correlograms using the conventional white light source and the dual wavelength white LED with the BY ratio of 1.60.

Using the phase-crossing algorithm, the height profiles measured with different light sources are reconstructed. Figure 10 compares the 1 μm step height measured by the phase-crossing algorithm [21,22] using the conventional white light source and the dual wavelength white LEDs. For an objective assessment, the measurement repeatability (in terms of the standard deviation in measuring the flat surface) and the accuracy of reconstructed profiles are further analyzed.

Figure 11 compares the phase-crossing algorithm using different light sources in terms of (a) the measurement repeatability and (b) the measurement accuracy. It shows that both the measurement accuracy and repeatability of the phase-crossing algorithm are improved when using the dual wavelength white LEDs.

Fig. 9. Comparing the correlograms using the conventional white light source and the dual wavelength white LED (BY ratio = 1.6).

Fig. 10. Comparing the simulated 1 μm step height measured by the phase-crossing algorithm [21,22] using (a) the conventional white light source and (b) the dual wavelength white LED with the BY ratio of 0.59, 1.14, and 1.60.

Fig. 11. Comparing the performance of the phase-crossing algorithm [21,22] using different light sources in terms of (a) the measurement repeatability (in terms of the standard deviation), the standard deviation of a perfectly flat surface is zero and (b) the measurement accuracy, the ideal value is 1 μm .

Fig. 12. Experimental verification that measured a 10 μm step height with the phase-crossing algorithm [21,22] using (a) the conventional white light source and (b) the dual wavelength white LED.

For experimental verification, we adopted the configuration similar to the earlier simulation but measured a WYKO $10.02 \pm 0.08 \mu\text{m}$ standard step height. Figure 12 compares the $10 \mu\text{m}$ step height measured by the phase-crossing algorithm [21,22] using the conventional white light source and the dual wavelength white LED with the BY ratio of 1.60 (LXHL-LW6C by LumiLEDs). The experimental result shows that the performance of the phase-crossing algorithm is improved by using the dual wavelength white LED: (1) In terms of the measurement repeatability, the standard deviation for measuring flat surface is 2.17 nm when using the dual wavelength white LED compared to 26.24 nm when using the conventional white light and (2) In terms of the measurement accuracy, the difference from the nominal value of the standard step height is smaller when using the dual wavelength white LED: the step height value is $10.09 \mu\text{m}$ when measured using the dual wavelength white LED compared to $10.18 \mu\text{m}$ when measured using the conventional white light. This result is consistent with the simulation result presented earlier.

7. Conclusion

In summary, we have modeled the spectral property and variation of dual wavelength white LED, followed by investigating its effects on the interference signal of vertical scanning interferometry. Essentially, the spectral variation of the dual wavelength white LED can be expressed in term of blue-to-yellow ratio (BY ratio) in its intensity spectrum.

Regardless of the spectral variation of the dual wavelength white LED, the dual wavelength white LED affects the interference signal of vertical scanning interferometry and that its fringe contrast

function can no longer be modeled as a single Gaussian function.

Instead of compensating the spectral effects of the dual wavelength white LED, we have identified and demonstrated that the spectral effects can be harnessed to improve the performance of the phase-crossing height reconstruction algorithm [21,22] in vertical scanning interferometry.

Future research will include designing the spectrum of the light source to improve the performance of vertical scanning interferometry.

Appendix A

The envelope of the interferogram is extracted by

1. Applying a Gaussian-based low pass filter (the cutoff wavelength = 400 nm). The value of the cutoff wavelength was determined empirically such that the extracted envelope represents the envelope of the original signal and doesn't have ripple.

2. After the low pass filter, the extracted envelope is scaled up to match the amplitude of the correlogram.

Appendix B

The detailed implementation of the phase crossing algorithm [21,22] is illustrated in Table 1.

Appendix C

It is found that the performance of the phase-crossing algorithm [21,22] is insensitive to the selection of the filter window (in terms of location and size) as long as there is one peak in each filter window. For verification, a simulation (a line profile of $1 \mu\text{m}$ step height is measured using a dual wavelength white LED with the BY ratio of 1.60)

Table 1. Illustrating the Detailed Implementation of the Phase-Crossing Algorithm [21,22]

Step	Description	Graphical Illustration
1	Input: a correlogram
2	A subset of the correlogram is extracted by finding the global peak, and the size of the subset is determined by evaluating the variance of the signal

(Table continued)

Table 1. Continued

Step	Description	Graphical Illustration
3	Apply fast Fourier transform to the subset selected in step (2)
4	Apply peak and valley detections algorithm to the output of step (3)
5	<p>Setting the filter windows based on</p> <ul style="list-style-type: none"> • The location and amplitude of the peaks and valley • The noise level of the signal <p>Appendix C discusses the sensitivity of the phase-crossing algorithm against the configurations of the filter windows</p>
6	<p>For each filter window, recover the phase information by Fourier transform method [23] that involves</p> <ol style="list-style-type: none"> Translating the filtered component to the origin (frequency = 0) Applying inverse Fourier transform to the translated signal The phase information is the imaginary part of the output of step (6b) <p>Here is a summary of the theory of doing so:</p> <ol style="list-style-type: none"> The interference signal is modeled is $g(z) = a + b(z) \cos(2\pi f_0 z + \phi(z))$ <p>where z is the defocus position and ϕ_0 is the phase</p> <ol style="list-style-type: none"> The signal is then rewritten as $g(z) = a(z) + c(z)e^{2\pi f_0 z i} + c(z)^* e^{-2\pi f_0 z i}$ <p>where $c(z) = \frac{1}{2}b(z)e^{\phi(z)i}$</p> <ol style="list-style-type: none"> The rewritten form of the signal is Fourier transformed with respect to z, and it gives $G(f) = A(f) + C(f - f_0) + C^*(f + f_0)$ <ol style="list-style-type: none"> By translating $C(f - f_0)$ by f_0 to the origin and applying the inverse Fourier transform, $c(z)$ is recovered. With $c(z)$, the phase information is recovered by applying a log operator: $\log(c(z)) = \log\left(\frac{1}{2}b(z)e^{\phi(z)i}\right) = \log\left(\frac{1}{2}b(z)\right) + \phi(z)i.$ <p>Please refer to Takeda <i>et al.</i> [23] for detail</p> 	
7	<p>Lastly, the phase-crossing point is recovered by</p> <ol style="list-style-type: none"> Applying linear fitting to each of the recovered phase signals Solving these two linear equations to find the intersection point 	

Table 2. Comparing the Performance of the Phase-Crossing Algorithm with Different Configurations of Filter Windows

Configuration of Filter Windows (Filter 1: Red •, Filter 2: Blue *)	Standard Deviation of Measuring Flat Surface (μm)	Measured Step Height (μm)
0.0067	1.002
0.0069	1.001
0.0063	1.001

has been conducted and the result is shown in Table 2.

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