Parameter Estimation of Structural Color by Spectral Measurement and Reproduction Using Spectral Projector

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ABSTRACT

This study estimated the normal, film thickness, and refractive index of structural color objects by thin-film interference using spectral measurements to reproduce structural color based on BRDF models. In addition, based on these estimated parameters, we spectrally reproduced structural colors using a spectral projector.

1 Introduction

Most of the object colors around us are caused by the surface reflectance of objects themselves, absorbing light of wavelengths other than the specified one. On the other hand, structural colors are caused by interference and diffraction of light entering the microstructure of objects. For example, there are structural colors by thin-film interference such as soap bubbles and oil films, structural colors by multilayer interference such as buprestids, and structural colors such as CDs in which the fine grooves on the surface play the role of diffraction gratings. One of the characteristics of structural colors is that spectral reflectance differs depending on an incident angle of a light source and a viewing angle, resulting in different visible colors. In order to reproduce images taking into account these structural color characteristics, functions that represent the reflection characteristics of an object at each angle, called BRDF (bi-directional reflectance distribution function) models, have been proposed in the field of computer graphics. However, in order to reproduce the color of a real object based on BRDF models, it is necessary to estimate the model parameters such as film thickness and refractive index of actual structural color objects.

In this study, therefore, we estimate the normal, film thickness, and refractive index of structural color objects by thin-film interference using spectral measurements. Furthermore, we substitute these estimated parameters into the BRDF model [1] and simulate the spectral reflectance at various incident angles of a light source and viewing angles. Based on these spectral reflectance, we spectrally reproduce structural colors at each angle using a spectral projector [2].

2 Theory of Parameter Estimation

2.1 Estimation of Film Thickness and Refractive Index

The method of film thickness and refractive index estimation is based on Kobayashi et al. [3]. Let R_m be the reflectance obtained by measurement and R_c be the reflectance calculated using the BRDF model of structural color by thin-film interference of Belcour et al. [1]. When the measured reflectance $R_m^1, R_m^2, \ldots, R_m^M$ measured at several different light source angles are obtained, let $R_c^1, R_c^2, \ldots, R_c^M$ be the reflectance calculated by the BRDF model equation at each light source angle. Then, the pair of film thickness and refractive index that minimizes equation (1) are the parameters of the target object.

$$E = \sum_{1}^{M} \{R_m^i - R_c^i\}^2 \tag{1}$$

In this study, in order to lower the calculation cost, the following constraints are applied to search for all pairs of film thickness and refractive index that minimize the squared error.

$$1.0 \leq n_2 \leq 3.0 \tag{2}$$
$$100 \leq d \leq 300[nm] \tag{3}$$

The refractive indices of common materials are within the range of equation (2). There are some materials with refractive indices above 3.0, but they are exceptional. The refractive index is the speed of light in a vacuum divided by the speed of light in a material, and it can never be less than 1.0. Therefore, the constraint in equation (2) was set. In addition, the structural color samples used in this study were fabricated with film thicknesses ranging from 100 [nm] to 300 [nm]. Therefore, the constraint in Equation (3) was also set for the film thickness. Given these constraints, and assuming that the medium on the incident side is an air layer (refractive index: 1.00), the pair of film thickness and refractive index that minimizes the squared error in equation (1) can be obtained.

2.2 Estimation of a Normal, Film Thickness, and Refractive Index

When an arbitrarily shaped object is illuminated using omnidirectional illumination, light is incident on a single point of the object from various directions. Suppose the object has a structural color due to thin-film interference. In that case, the intensity of the specular reflection (intensity of reflection in the specular reflection direction) is much higher than that of the diffuse reflection (intensity of reflection in the negative reflection direction), so the intensity of the reflected light observed at one point can be approximated to the value of the specular reflection only. Also, the spectral distribution of specular reflection light from a thin-film structural color object depends on the magnitude of the specular reflection angle. The intensity decreases as the specular reflection angle increases when the object is irradiated with p-polarized light. Therefore, we can assume that the specular reflection light with the highest intensity among the measured specular reflections is the specular reflection light with a specular reflection angle of 0°, and the one with the lowest intensity is the specular reflection light with a specular reflection angle of 90°. By doing so, the film thickness and refractive index can be estimated using the method described in Section 2.1. Furthermore, the normal direction can be estimated from the spectral distribution of specular reflection light by finding the magnitude of the specular reflection angle that minimizes the error between the spectral distribution calculated by substituting the estimated film thickness and refractive index BRDF model and the measured spectral distribution.

3 Measurement Experiment

3.1 Measurement Environment and Setting

The structural color samples used in this study are shown in Figure 1. The sample is a stainless steel oxidized chromogenic (Nakano Science) plate. The shape is a square with a side length of 50 mm. A 2D spectroradiometer SR-5000 (TOPCON) was used as a camera. The wavelength resolution is 380 nm to 780 nm (5 nm). The light source is a HOLOLIGHT parallel illumination type (PiPHOTONICS). The measurement environment is shown in Figure 2. The distance between the sample and the camera was 650 mm, and the distance between the sample and the light source was 400 mm.

The measurement setup is shown in Figure 3. In this study, the camera angle is fixed at 0°, the angle between the camera direction and the normal of the structural color sample (from now on referred to as the sample angle) is set to 5° to 45° (in 10° increments), and the light source angle is set to 10° to 90° (in 10° increments). Then, we measure the reflected light when the light is irradiated to an arbitrarily shaped object using virtual omnidirectional illumination by taking 45 measurements (5×9).

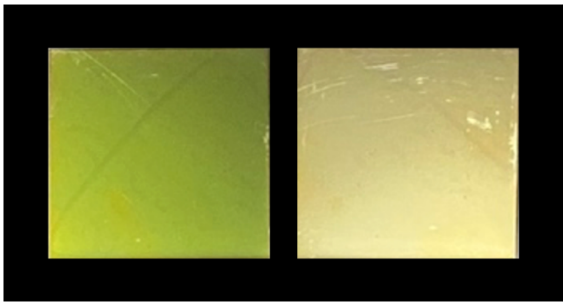


Fig. 1 Structural color samples
(Left: Sample Green, Right: Sample Gold)

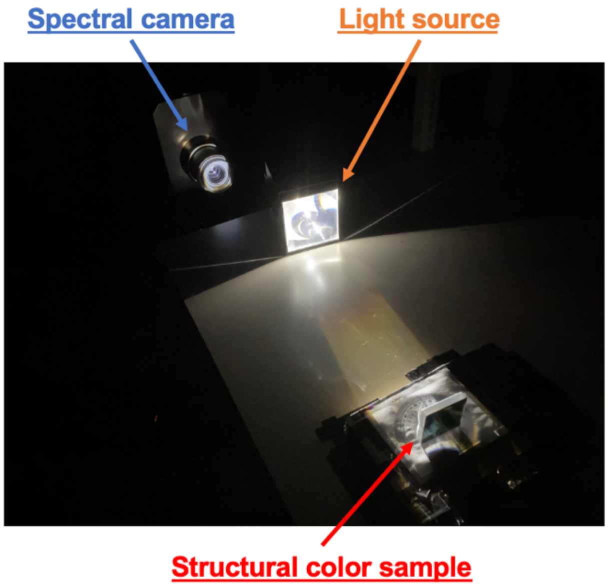


Fig. 2 Measurement environment

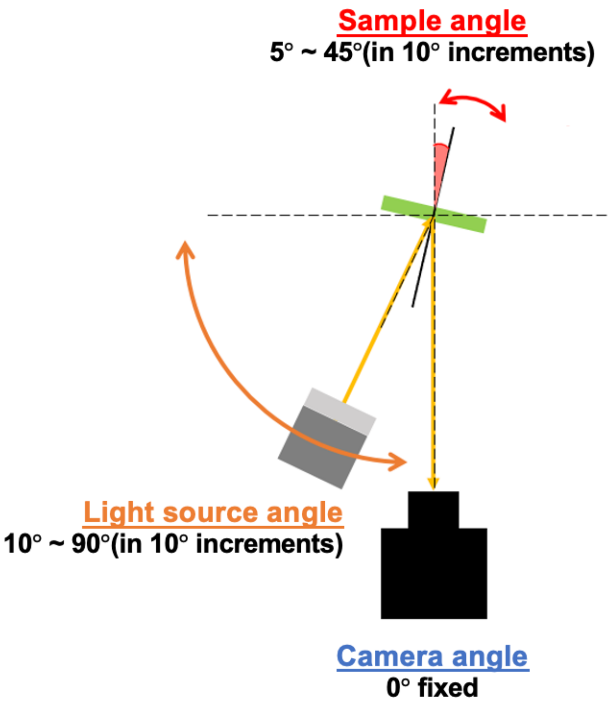


Fig. 3 Schematic of the measurement setup

3.2 Results of Measurement and Procedure for Estimating Parameters

Figure 4 shows the measurement results of the reflectance of the sample Green and the procedure to estimate the parameters. The highest value of specular reflection light is assumed to be the specular reflection light at an incident angle of 5° - reflection angle of 5° (specular reflection angle is 5°), and the lowest value of specular reflection light is assumed to be the specular reflection light at an incident angle of 45° - reflection angle of 45° (specular reflection angle is 45°). Using those two measurements, we estimate the film thickness and refractive index using the method described in Section 3.1, and substitute the estimated parameters into the model equation. Then, the sample angle (normal direction) of other specular reflection lights are estimated by estimating the magnitude of the specular reflection angle that minimizes the squared error between the measured value and the model value.

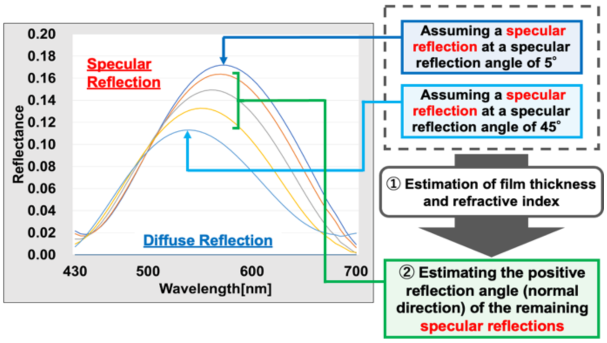


Fig. 4 Measurement results of sample Green and parameter estimation flow (It can also be seen that the intensity of the diffuse reflected light is fragile.)

3.3 Results of Parameter Estimation

The thickness and refractive index of the structural color samples were estimated using the method described in Section 2.1. The thickness and refractive index of sample Gold were 151 [nm] and 1.76, respectively, and the thickness and refractive index of sample Green were 274 [nm] and 1.95, respectively. Figure 5 and Table 1 show the results of model fitting and RMSE of specular reflection light at 5° and 45° of specular reflection angle using these parameters. Looking at Fig. 5, a large discrepancy between the measured and model values in the high-frequency part of the specular reflection angle of 45°. However, we considered that the model fitting was sufficiently accurate, and we used these parameters to estimate the sample angle.

Table 2 shows the results of using the estimated parameters to estimate the sample angles of the other three specular reflection lights. From the results, we can see that the sample angle can be estimated within 2° error for sample Green and within 3° error for sample Gold.

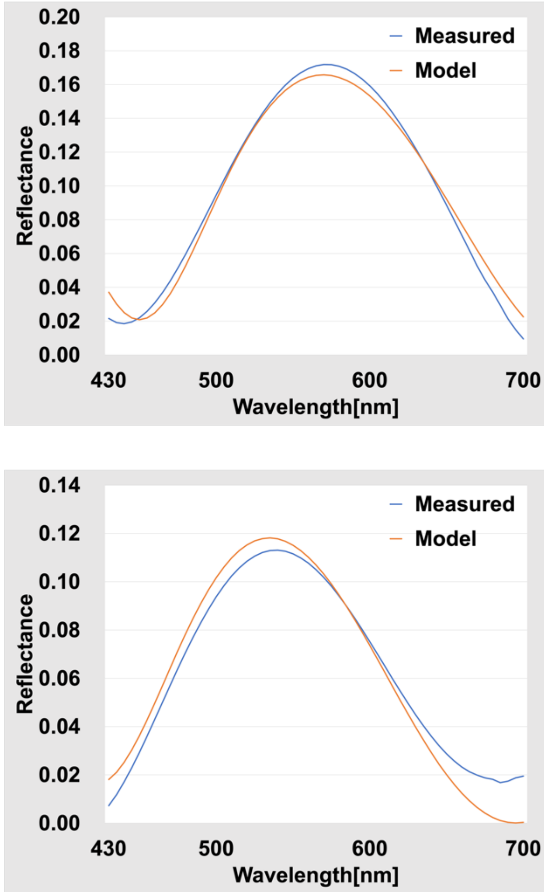


Fig. 5 Fitting result of sample Green
(Top: specular reflection angle 5°, Bottom: 45°)

Table 1 RMSE for each angle of specular reflection

	Specular reflection angle 5°	45°
Green	0.0065068	0.0083856
Gold	0.0025990	0.0042812

Table 2 Estimated sample angles

	Sample angle15°	25°	35°
Green	17°	27°	37°
Gold	18°	26°	36°

4 Reproduction of Structural Colors using a Spectral Projector

Figure 6 shows how the spectroscopic projector [2] reproduces the appearance of the structural color sample when an incandescent light bulb is illuminated at a specific angle. Projection reproduction was performed for one specific light source angle and one specific observation angle, and a white plate was used as the screen. Figure 7 shows the projected spectral distribution. The spectral distribution can be obtained by multiplying the spectral reflectance of the incandescent lamp by the spectral reflectance of the light source at the various incidence and observation angles, which can be obtained by substituting the estimated parameters BRDF model.

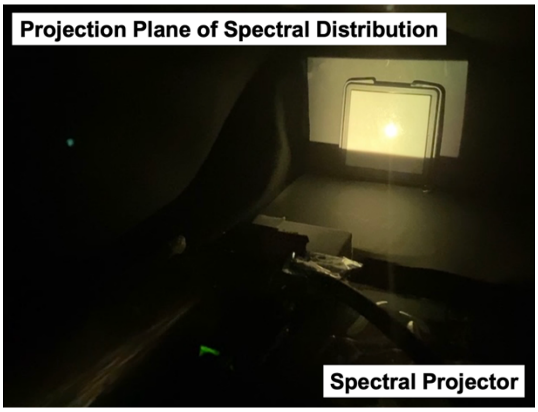


Fig. 6 Projection reproduction of structural colors by a spectral projector

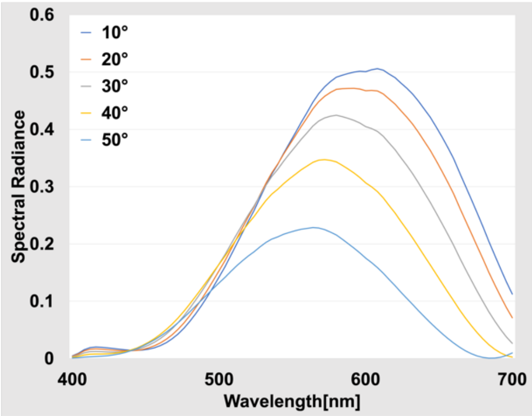
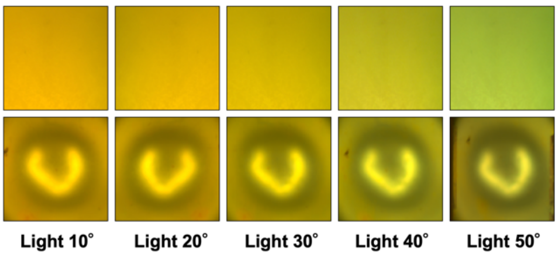
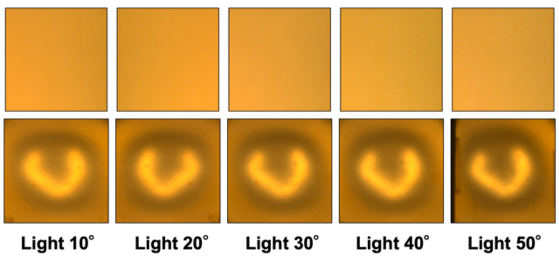


Fig. 7 Spectral distribution used to reproduce the sample Green.



(a) Sample Green



(b) Sample Gold

Fig. 8 Reproduction results of structural colors at different light source angles

(Top: Reproduction using a spectroscopic projector; Bottom: Actual irradiation of an incandescent lamp. Note that the shape of the incandescent bulb is reflected in the image irradiated by the incandescent bulb.)

Figure 8 compares the structural colors reproduced at different light source angles and the structural colors observed when an incandescent lamp is irradiated. The results show that we were able to reproduce the characteristics of the structural colors, which are slightly different colors depending on the light source angle. However, the color of the sample Green at a light source angle of 50° seems to be slightly different from the actual color. As you can see in Fig. 5, the reason for this is that the deviation between the measured and model values in the high-frequency part of the fitting result of sample Green has a non-negligible effect at a light source angle of 50°.

5 Conclusion

In this paper, we used a spectral camera to measure the spectral reflectance of a structural color object. We estimated the normal, film thickness, and refractive index of the structural color object based on the measurement results. The normal direction was estimated within 2° error for sample Green and within 3° error for sample Gold. Also, based on the estimated film thickness and refractive index, the structural color was reproduced spectrally using a spectral projector. From the results, it was confirmed that the angular dependence of the structural color could be reproduced.

As future work, we would like to extend the measurement target to 3D objects and estimate the parameters of 3D objects, since this study was limited to 2D planar objects. In addition, we would like to verify the accuracy of the parameter estimation by using samples with known film thickness and refractive index.

References

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