Measurement and Modeling of Bidirectional Characteristics of Fluorescent Objects

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Abstract. A method is proposed for measurement and modeling of bidirectional characteristics of fluorescent objects. First, a gonio-spectro measurement system is constructed for measuring the spectral luminescent radiance factor of a variety of fluorescent object surfaces. Second, the angular dependency of the luminescence radiance factor is analyzed in different light incidence and viewing directions. The observed radiance factors can then be described by the Lambertian model with good accuracy. We also analyze the bidirectional reflection radiance factor of a white mat surface. The whole characteristics of bispectral bidirectional radiance factors of a fluorescent object can be summarized as a compact mathematical model. Finally, image rendering of a fluorescent object is performed using the Donaldson matrix estimated in a separate measurement system. The feasibility of the proposed method was examined experimentally.

Keywords: Fluorescent object, bispectral bidirectional radiance factor, measurement and modeling.

1 Introduction

The luminescent radiation effect of fluorescent objects improves the visual appearance of object surfaces. In particular, many fluorescent surfaces appear brighter and more vivid than the original color surfaces. For this reason, fluorescent materials are important and attractive as research objects of imaging science and technology [1]-[3]. In these days fluorescent substance applies to many common materials, for instance paints, plastics, papers, cloths, or even human teeth. Therefore, the appearance of fluorescent objects is analyzed in the field of computer vision and image processing [4]-[5]. The appearance synthesis is studied in computer graphics [6]-[7].

Knowing the bispectral characteristics of a fluorescent object is important. The spectral radiance factor of a fluorescent material consists of the sum of two components: a reflected radiance factor and a fluorescent (luminescent) radiance factor. Such fluorescent characteristics can be measured accurately by the two-monochromator method [8]. The results of bispectral measurements are summarized as a Donaldon matrix, which is an illuminant independent matrix representation of the bispectral radiance factor of a target object. However the two-monochromator method

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is expensive, and is only available in laboratory setup, but not in natural scene. In a previous paper [5], the authors proposed a method for estimating a generalized bispectral matrix for fluorescent objects. The Donaldson matrix was constructed on the wide wavelength range over both ultraviolet and visible wavelengths. We presented an algorithm for estimating precisely the general shape of luminescent radiance component as a function of excitation wavelength.

Knowing the bidirectional characteristics of a fluorescent object is crucial as well as knowing the bispectral characteristics. The appearance of a fluorescent object is considered to be composed of both the ordinary reflection factor and the fluorescent emission factor. The reflection factor is normally decomposed into the diffuse reflection component and the specular reflection component. It should be noted that all these factors are the functions of angles such as viewing angle and the angle of light incidence. That is, the appearance of a fluorescent object is angularly dependent. Image rendering for producing the appearance of fluorescent objects will not be realized without models for reflection and emission of the objects. The reflection component is considered to be characterized by a bidirectional reflectance distribution function (BRDF). On the other hand the emission component of fluorescence was sometimes assumed as the Lambertian model [7],[10]. However, there has been no experimental evidence provided to show the validity of the model for a variety of materials.

The present paper proposes a method for measurement and modeling of the bidirectional characteristics of fluorescent objects. First, a gonio-spectro measurement system is constructed for measuring the spectral luminescent radiance factor of a fluorescent object surface. We use flat samples of different fluorescent materials, including paints, papers, and plastics. Second, we analyze the angular dependency of the luminescence radiance factor measured in different light incidence and viewing directions. Then it is shown that the observed radiance factors can be described by a mathematical model with good accuracy. We also measure the bidirectional reflection radiance factor of a white mat object surface, and analyze the angular dependency by changing the light incidence and viewing directions. The bidirectional characteristics of fluorescent objects are summarized as a compact mathematical model. Finally, image rendering of fluorescent objects are performed based on a bispectral bidirectional reflection and luminescence model. The feasibility of the proposed method is examined in the experiments with image rendering results.

2 Measurement of Fluorescent Objects

2.1 Measuring System

Figure 1 shows the geometry for measuring surface properties of a fluorescent object. An ultraviolet light (black light) source was used as a light source. The LED black light lamp used in this study has a sharp directionality, and it can be considered a point light source. The spectral distribution is a very narrow band with the peak at 375 nm. This monochromatic property makes it possible to measure only the lfluorescent emission component from a target object surface.

A spectro-radiometer (Photo Research, PR650) was used for luminance measurement of the same fluorescence object surface. The meter was placed at a distance of 80 cm from the surface, and the measured area was a diameter of about 1 cm, corresponding to a visual field of 0.3 degree. We also measured a white standard plate by this meter. The luminescent radiance factor was determined as a relative luminance value by taking the ratio between the luminance measured for a target surface and the luminance measured for the white reference.

The targets for measurement were fluorescent objects with a flat surface. We selected twelve objects, consisting of different materials, which were color board (yellow), sticker (green), paint (red), fluorescence papers (red, green, yellow), fluorescence sheets (red. green, yellow), and fluorescence tapes (red, green, yellow). The emission characteristics of each surface were measured with a combination of 17 viewing angles θ_v (-80, -70, …, -10, 0, 10, …, 70, 80 degrees) and 17 incidence angles θ_i (-80, -70, …, -10, 0, 10, …, 70, 80 degrees).

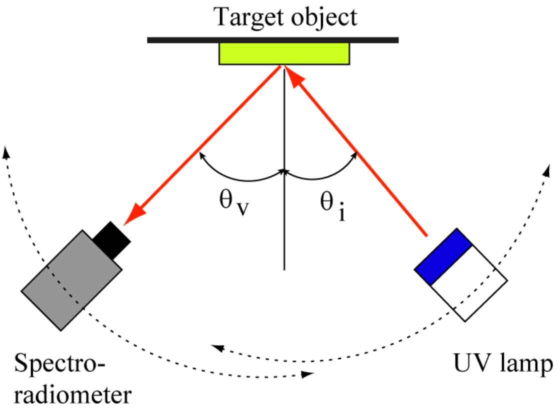
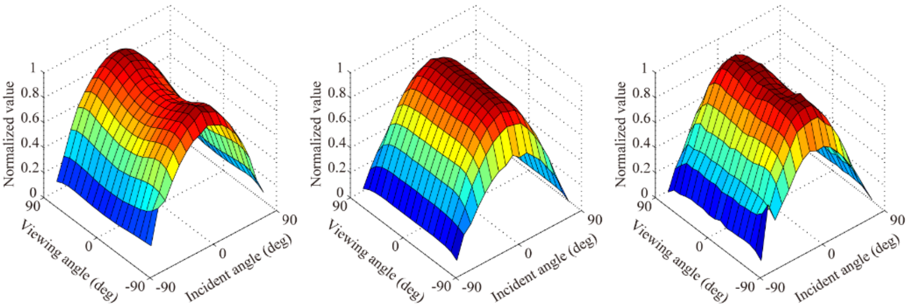


Fig. 1. Geometry for measuring surface properties of a fluorescent object

2.2 Measurement Results

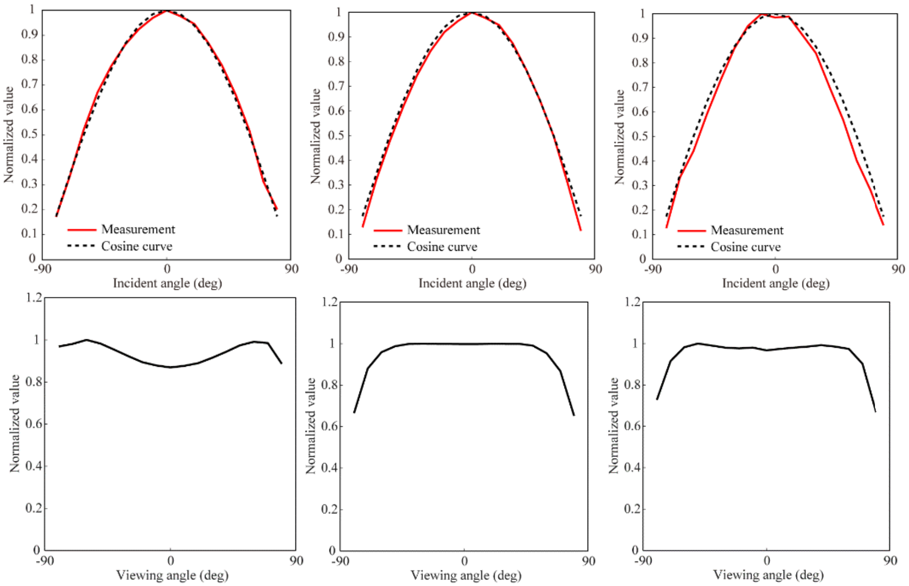
The spectral radiance factors of all objects were measured by changing both the incident and viewing angles. Figure 2 shows the radiance factors measured from three representative objects of a green fluorescence paper, a yellow fluorescence sheet, and a red fluorescence tape. The figure represents a three-dimensional (3D) perspective view where the radiance factor is depicted as a function of both angles of incidence and viewing. The spectral radiance factor can originally be measured using a function of wavelength. However, since the fluorescence radiation has emission at a specific wavelength in the visible range [400, 700], we integrate the spectral radiance factor over the specific wavelength to obtain the summarized value independent of wavelength. Note that we have no measurements at the angular condition of θ_v = - θ_i because the sensor (spectro-radiometer) angel is the same as the light source. A Spline function was fitted to the measured radiance factors in order to interpolate the data points.

Both angles of viewing and incidence are important parameters in analyzing the directional characteristics of the luminescent radiance factor. To clarify this, the 3D graphs of the radiance factors in Figure 2 were projected onto the respective axes of the incidence angle and the viewing angle. In other words, the radiance factors were averaged over the viewing angle and the incidence angle, separately. Then, two types of the average radiance factors were represented separately as a function of the viewing angle and as a function of the incident angle. These figures are shown in Figure 3. The left and right figures in Figure 3 show the angular dependency concerning the incident angle and viewing angle, respectively.



(a) Green fluorescence paper (b) Yellow fluorescence sheet (c) Red fluorescence tape

Fig. 2. Radiance factors measured by changing the incident and viewing angles



(a) Green fluorescence paper (b) Yellow fluorescence sheet (c) Red fluorescence tape

Fig. 3. Radiance factors measured by changing incident and viewing angles

3 Modeling of Bidirectional Characteristics

We consider mathematical description of the luminescent radiance factor of fluorescent objects. Figures 2 and 3 suggest that the observed luminescent radiance factors are separable into a function of the viewing angle and a function of the incident angle. This separable property makes the mathematical modeling simple. The 2D characteristics of the luminescent radiance factor can be summarized into multiplication of two types of the function with a single variable of angle as $f(\theta_V)f(\theta_i)$. The left figures in Figure 3 depict changes of the luminescent radiance factor due to different lighting directions. We find that the observed data of the luminescent radiance factor are well fitted to a cosine function. On the other hand, the right figures in Figure 5 depict the changes of the radiance factor due to different viewing directions. The observed values are almost constant except for the extreme edge angles close to -90 and +90.

Let **L** and **V** be the vectors indicating the light source direction and the viewing direction, respectively. Then, the luminescent radiance factor is proportional only to the cosine of incident angle, independently of the viewing angle. This characteristic is similar to the reflection property for the surface of a perfect diffuser, call Lambertian surface. However, note that a fluorescent object is bispectral, differently from usual object without fluorescence. Let $S(\lambda_{out},\lambda_{in})$ be the bispectral radiance factor, where λ_{out} and λ_{in} are the excitation (input) and emission (output) wavelengths, respectively. The bispectral radiance factor is composed of the sum of two components: the luminescent radiance factor and the reflection radiance factor as

$$S(\lambda_{out},\lambda_{in})=S_l(\lambda_{out},\lambda_{in})+S_r(\lambda_{out},\lambda_{in}) \ . \tag{1}$$

In the luminescent factor $S(\lambda_{out},\lambda_{in})$, the emission wavelength is longer than the excitation wavelength, $\lambda_{out}>\lambda_{in}$, and in the reflectance factor $S(\lambda_{out},\lambda_{in})$, the excitation and emission wavelengths are equal, $\lambda_{out}=\lambda_{in}$. Therefore, the bispectral luminescent radiance factor can be described as

$$Y_l(\mathbf{V},\mathbf{L},\lambda_{out},\lambda_{in})=S_l(\lambda_{out},\lambda_{in})\cos\theta_i\, E(\mathbf{L},\lambda_{in}) \ , \tag{2}$$

where $E(\mathbf{L},\lambda_{in})$ is the spectral-power distribution of illumination incident from the direction **L**.

Concerning the reflection radiance factor, we cannot analyze the bidirectional reflection characteristics of a fluorescent object accurately without the luminescent radiance factor. The observations should always include the luminescent component. In this paper, we investigate the flection characteristics of non-fluorescent matte object which has similar surface appearance to a fluorescent object. A matte object called Spectralon providing near-perfect diffuse reflectance was used as a target object. Figure 4 depicts the average values of the measured reflection radiance factors as a function of the incident angle and a function of the viewing angle. In the left figure, the measurements of the reflection radiance factor are represented approximately using a cosine function of the incident angle. However, this functional fitting is not sufficient. On the other hand, in the right figure, the reflection radiance factor is independent of the viewing angle. Compare Figure 4 with Figure 3. In Figure 3 the luminescent component of a fluorescent object is emitted uniformly in all directions of θ_v, and it behaves like a perfect diffuser. Nonetheless, the diffuse reflection component of an inhomogeneous dielectric object is usually represented using the Lambertian model. Therefore, by incorporating the spectral reflectance, we describe the spectral reflection radiance factor as

$$Y_d(\mathbf{V},\mathbf{L},\lambda_{out},\lambda_{in}) = S_r(\lambda_{out})\,\delta(\lambda_{out}-\lambda_{in})\cos\theta_i\, E(\mathbf{L},\lambda_{in}), \tag{3}$$

where δ is the Dirac delta function.

Light reflection from a fluorescent object surface often includes the specular (interface) reflection component. In this paper, we suppose that the specular reflection component has the same property as an inhomogeneous dielectric object. The Torrance-Sparrow model describes precisely the specular reflection component [10]. The spectral reflection radiance factor is modeled as

$$Y_s(\mathbf{V},\mathbf{L},\lambda_{out},\lambda_{in}) = c_s \frac{D(\varphi)G(\mathbf{V},\mathbf{L})F(\theta_Q,n)}{\cos\theta_r}\delta(\lambda_{out}-\lambda_{in})E(\mathbf{L},\lambda_{in}), \tag{4}$$

where c_s is a coefficient representing specular intensity, D is the distribution function of the microfacet orientation, G is the geometric attenuation facto, and F represents the Fresnel spectral reflectance of the microfacets. If we let **Q** be the bisector of **L** and **V** vectors, θ_Q is the angle between **L** and **Q**, and φ is the angle between **Q** and the surface normal **N**.

Thus, the whole characteristics of bispectral bidirectional radiance factors of a fluorescent object can be summarized in the form $Y = Y_l + Y_d + Y_s$.

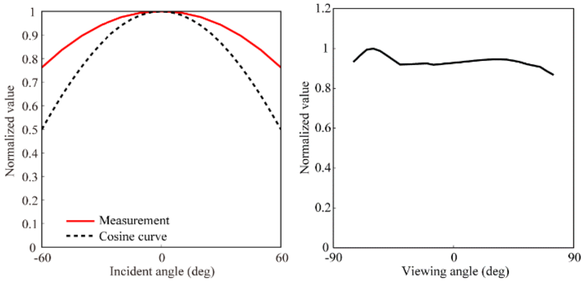


Fig. 4. Reflection radiance factor as a function of the incident angle

4 Image Rendering

For spectral rendering of fluorescent objects, we require the Donaldson matrix representing the bispectral radiance factor of the fluorescent objects. The Donaldson matrix can be estimated by the previous method [3] based on the use of two visible light sources with continuous spectral-power distributions. A fluorescent paint ‘Lumi Yellow’ applied on a paper was selected as a fluorescent sample object.

Figure 5 shows the estimated Donaldson matrix of Lumi Yellow. An incandescent lamp and an artificial sun lamp were used in estimating the Donaldson matrix. The luminescent radiance factor $S_l(\lambda_{out}, \lambda_{in})$ and the reflectance factor $S_r(\lambda_{out}, \lambda_{in})$ of the bispectral radiance factor can be determined from the Donaldson matrix shown in Figure 5.

We have rendered a sphere painted with Lumi Yellow under a uniform illumination of the artificial sun lamp. Figure 6 (a) demonstrates the rendered object based on Eq.(8), where both the light source and the viewing point are positioned in the front of the object. The rendered object image is decomposed into three component images. Figures 6(c), (c), and (d) show, respectively, the luminescent emission component, the diffuse reflection component, and the specular reflection component. We should note that the component image of luminescent emission represent a unique characteristic image of the fluorescent object, which clearly differ from the other component images. The specular component image was created using the parameter values of 0.05 for the surface roughness, 1.45 for the index of refraction, and 30.0 for specular intensity coefficient. The specular image represents a highlight area on the surface with the illumination color.

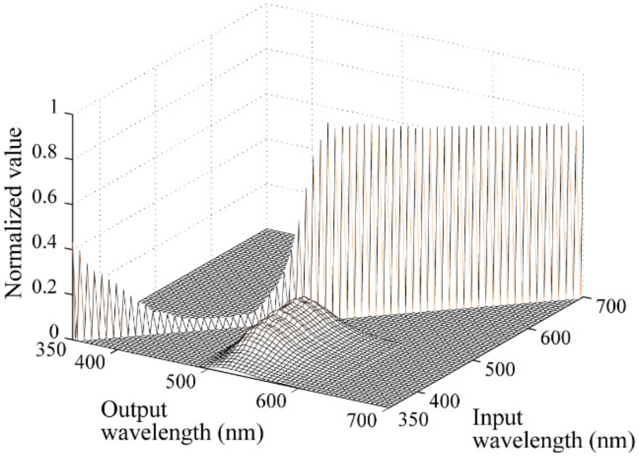
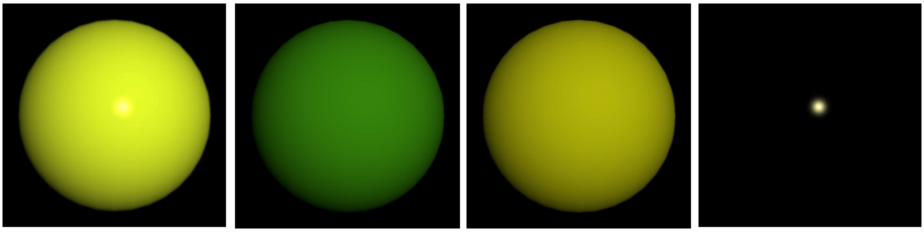


Fig. 5. Estimated Donaldson matrix of Lumi Yellow

5 Conclusion

This paper has proposed a method for measurement and modeling of bidirectional characteristics of fluorescent objects. First, a gonio-spectro measurement system was constructed for measuring the spectral luminescent radiance factor of a variety of fluorescent object surfaces. Second, we analyzed the angular dependency of the luminescence radiance factor at different light incidence and viewing directions.

The observed radiance factors could then be described by the Lambertian model with good accuracy. We also analyzed the bidirectional reflection radiance factor of a white mat object surface. The whole characteristics of bispectral bidirectional radiance factors of a fluorescent object could be summarized as a compact mathematical model. The model is independent of illumination. Finally, image rendering of a fluorescent object was performed using the Donaldson matrix. The feasibility of the proposed method was confirmed experimentally.



(a) (b) (c) d)

Fig. 6. Sphere painted with Lumi Yellow rendered under the artificial sun lamp. (a) Rendered object, (b) Luminescent emission component, (c) Diffuse reflection component, (d) Specular reflection component.

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