Illumination uniformity optimization of position-sensitive detector sensing optical system by circular and annular obscurations

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In order to increase the illumination uniformity of the position-sensitive detector (PSD) in a sensing optical system, an optimization method is introduced in this paper. The ratio of the oblique ray section to the paraxial ray section is adjusted by circular and annular obscurations with different parameters; thus, the relative illumination on the image plane can be optimized. In our case, the size and position of the circular and annular obscurations are optimization variables. The result shows illumination uniformity on a PSD is enhanced from the original 12%–69.7%, and the precision is greatly improved. The method in this paper is proved to be effective and low cost and to have potential in many other applications. © 2012 Optical Society of America

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1. Introduction

Illumination uniformity of an optical system is very important in many applications [1,2]. In position-sensitive detector (PSD) sensing, reimaging optical systems are usually used to enlarge detecting area. However, the illumination of the image plane becomes very nonuniform at the same time because of off-axis illumination descending of the lens and Gaussian scattering of the ground glass screen. This nonuniformity of illumination badly influences the accuracy of PSD sensing.

There are several illumination optimization methods. A gradient neutral density filter assembled far away from aperture stop's position is usually used to make the image plane's illumination uniform, which depresses the paraxial field's transmittance more than oblique [3]. However, the filter with complex coating is difficult to fabricate especially when it is large. Another way is to adapt a screen with special microconfigurations, which can give a better scattering property than ground glass [4], but it is difficult to fabricate too. Furthermore, if the lens is replaced by a designed optical system that is telecentric both in object and image space, the illumination uniformity of image plane can be improved [5]. But such an optical system will be very complicated and extraordinarily large due to the object or image plane's area.

A novel illumination uniformity method using circular and annular obscurations, which can significantly enhance illumination uniformity, is introduced in this paper. Compared with the general methods above, the method in this paper is simple, low cost, and effective in getting the same or even better illumination uniformity. In the example, a simple optical system with two singlet lenses is adapted to reimage in PSD sensing, and its image plane's illumination uniformity is increased from the original 12%–69.7% using this obscuration method.

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2. PSD Sensing Optical System

A. Principle and Requirement

PSDs are an important class of optoelectronic sensors that can detect the position of incident light using the lateral photoeffect [6]. When a laser beam is incident at some point of the PSD's sensitive surface, current I_1 and I_2 flowing toward both side electrodes are produced. By measuring current intensity of I_1 and I_2, light spot's position d can be calculated by [7]

$$d = \frac{D}{2}\frac{I_2 - I_1}{I_2 + I_1}, \tag{1}$$

where D is the length of the sensitive surface of the PSD. The light spot's position is only related to the current intensity in Eq. (1), but in real cases, because of the device and amplifying circuit's characteristics, the positioning accuracy not only depends on its electronic parameters but also can be influenced by illumination, diameter, and angle of incident light, especially the illumination [7–9]. Experiments have shown that the standard deviation of PSD measurements is less than 2 μm when the illumination's uniformity on the entire sensitive surface is above 50% but increased to 150 μm when illumination's uniformity is less than 20% [9]. Therefore, it is necessary to improve the uniformity in order to obtain high PSD precision.

B. Nonuniformity of Illumination in PSD Sensing Optics

Limited by manufacturing techniques, the detecting area of PSDs is small, which limits their application in real cases. The reimaging system shown in Fig. 1 can improve the detecting area. However, the illumination on PSD becomes nonuniform, which worsens the positioning accuracy.

As a classical optics' law, when a Lambertian plane is imaged by an ideal lens, illumination off the axis descending of its image plane can be described by

$$E'(\omega) = E'_0 \cdot \cos^4 \omega, \tag{2}$$

where E'_0 is paraxial illumination and ω is the angle of the chief ray.

In fact, the reception screen in use is hardly to be Lambertian. For example, ground glasses usually have a Gaussian-type scattering property. For a normal incident laser in Fig. 2, the flux is concentrated near the normal line after ground glass' scattering and attenuated fast with the viewing angle on the other side. The speed of this attenuation is relative to ground glass' roughness. So the illumination of laser flux into the lens in Fig. 1 can also be described by a function $E''(\omega)$. Considering both factors of lens and ground glass, the total illumination on PSD is

$$E_{\mathrm{PSD}}(\omega) = E'(\omega) \cdot E''(\omega). \tag{3}$$

Equation (3) shows the illumination uniformity of the PSD sensing system is inevitable, whether the

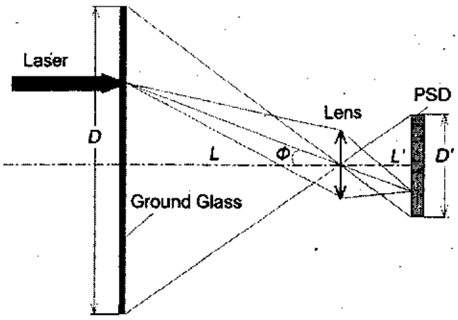

Fig. 1. (Color online) Principle of PSD sensing optics.

reimaging optical system is a singlet lens or a Gaussian-type lens. Considered aberration correction and optical path length, a symmetrical optical system composed of two singlet lenses is taken for an example in some PSD sensing devices (shown in Fig. 2). A 100 mm^2 detecting area is acquired in front using a 20 mm^2 PSD. The marginal field angle of this system is 17.5°. Relative illumination descending distributed by lens and ground glass is shown in Fig. 3. The ground glass is offered in 220 grit polishes, and its normalized $E(\omega)$ is given by measurements. The total relative illumination is plotted in Fig. 3. Most of the off-axis illumination descends due to ground glass, which results in the loss of precision. The total relative illumination of the marginal field is only 12% of the paraxial field in this case.

3. Optimization of Illumination Uniformity by Obscurations

A. Principle

When the lens is vignetting, the illumination formula of PSD sensing optics is [10]

$$E_{\mathrm{PSD}}(\omega) = E'(\omega) \cdot E''(\omega) = K_a(\omega) \cdot E'_0 \cdot \cos^4 \omega \cdot E''(\omega), \tag{4}$$

where $K_a(\omega)$ is the ratio of the oblique ray section to the paraxial ray section.

Supposing illumination on the PSD is uniform, we can get

$$\frac{E_{\mathrm{PSD}}(\omega)}{E'_0} = K_a(\omega) \cdot \cos^4 \omega \cdot E''(\omega) = 1, \tag{5}$$

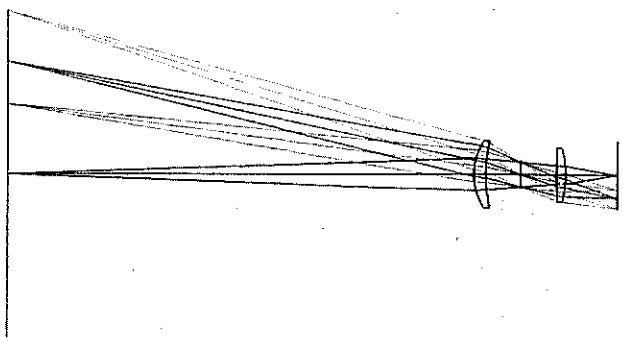

Fig. 2. (Color online) Layout of PSD sensing lens.

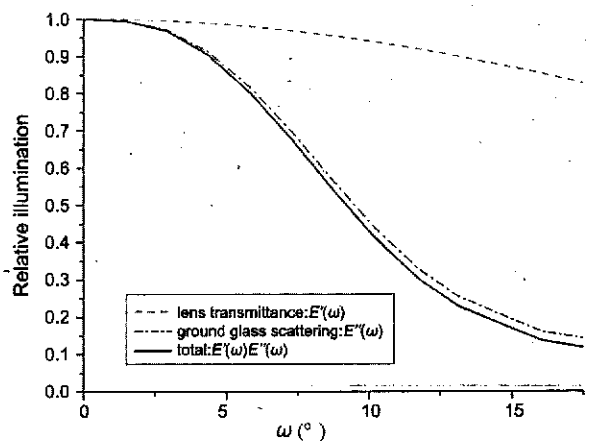

Fig. 3. (Color online) Relative illumination of original system.

then

$$K_a(\omega) = \frac{1}{\cos^4 \omega \cdot E''(\omega)}. \quad (6)$$

Obviously, if $K_a(\omega)$ satisfies Eq. (6), we can make illumination uniform.

Generally, vignetting of the optical system is caused by the lens' edge or mechanical frame, and the obscured area of marginal rays is larger than paraxial, which means the larger ω, the smaller $K_a(\omega)$. But the obscured area of marginal rays is smaller than paraxial when a circular obscuration is located in the field center far from aperture stop's position [11], which means the larger ω, the larger $K_a(\omega)$. Besides, an annular obscuration far from aperture stop's position can also adjust $K_a(\omega)$ by obscuring oblique rays between the paraxial field and the marginal. Therefore, combination of several circular and annular obscurations may properly make $K_a(\omega)$ close to Eq. (6). Optimization illumination of the PSD sensing optical system using obscurations is investigated in this paper.

B. Effects of Circular and Annular Obscurations

An infinite conjugate ideal optical system is taken as an example, in which the obscuration is located with distance being l to the entrance pupil; the distance between the center of obscuration and the center of the ray section with field angle ω is

$$d = l \tan \omega. \quad (7)$$

Relative positions of the circular obscuration and oblique ray section in rectangular coordinates are shown in Fig. 4, and point O is the center of obscuration. The paraxial field rays cannot be obscured completely in the actual design; we have $r < R$.

There is no oblique ray vignetting in an ideal optical system, which means the areas of the paraxial and oblique ray sections are the same when there is no obscuration. When there exists a circular obscuration, the ratio of the oblique ray section to the paraxial ray section K_a can be described as follows:

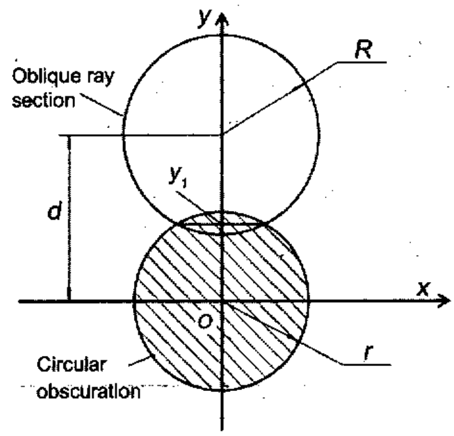

Fig. 4. Relation of oblique ray section and circular obscuration.

$$\begin{cases} K_a = 1 & d > R + r \\ K_a = \frac{R^2 - r^2}{R^2} & d < R - r \\ K_a = \frac{\pi R^2 - S_1}{\pi R^2} & R - r < d < R + r \end{cases}, \quad (8)$$

where S_1 is the overlapping areas of circular obscuration and ray section, which is calculated by

$$\begin{cases} S_1 = 2\left(\int_{d-R}^{y_1} \sqrt{r^2 - (d-y)^2} \cdot \mathrm{d}y + \int_{y_1}^{r} \sqrt{R^2 - y^2} \cdot \mathrm{d}y\right) \\ y_1 = \frac{R^2 + d^2 - r^2}{2d} \end{cases}. \quad (9)$$

Relations between the field angle and the K_a of circular obscuration with different r are shown in Fig. 5. It is shown that the larger the obscuration, the smaller the K_a of the paraxial field and the wider the K_a curve changing ranges will be. The common trends are that K_a become larger with an increasing field angle. So we know that illumination descending of the paraxial field caused by circular obscuration is more than oblique fields, and this descending is adjustable.

Then the annular obscuration's adjustive characteristic to K_a is investigated too, as shown in Fig. 6.

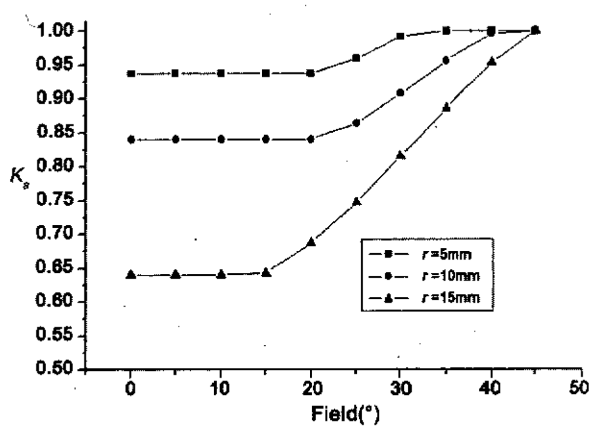

Fig. 5. K_a of circular obscuration versus field ($R = 25$ mm, $l = 40$ mm).

Paraxial field rays are supposed to be unobscured, and rays of any oblique field are not obscured completely, so we have $r_i > R$ and $r_o - r_i < R$. Similarly, K_a can be described as

$$\begin{cases} K_a = 1 & d > R + r_o \\ K_a = \frac{\pi R^2 - S_2}{\pi R^2} & R + r_i < d < R + r_o \\ K_a = \frac{\pi R^2 - S_3}{\pi R^2} & r_o - R < d < R + r_i \\ K_a = \frac{\pi R^2 - S_4}{\pi R^2} & r_i - R < d < r_o - R \\ K_a = 1 & d < r_i - R \end{cases}, \tag{10}$$

where S_2, S_3, and S_4 are the overlapping area of annular obscuration and ray section in different conditions, which are calculated as

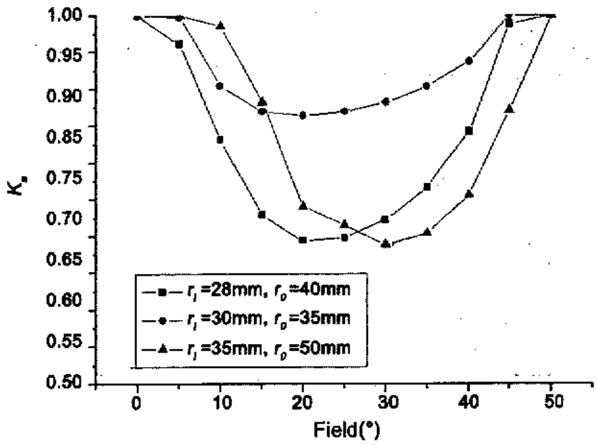

Fig. 7. K_a of annular obscuration versus field ($R = 25$ mm, $l = 40$ mm).

$$\begin{cases} S_2 = 2\left(\int_{d-R}^{y_o} \sqrt{r_o^2 - (d-y)^2} \cdot \mathrm{d}y + \int_{y_o}^{r_o} \sqrt{R^2 - y^2} \cdot \mathrm{d}y\right) \\ S_3 = 2\left(\int_{d-R}^{y_o} \sqrt{r_o^2 - (d-y)^2} \cdot \mathrm{d}y + \int_{y_o}^{r_o} \sqrt{R^2 - y^2} \cdot \mathrm{d}y\right) - 2\left(\int_{d-R}^{y_i} \sqrt{r_i^2 - (d-y)^2} \cdot \mathrm{d}y + \int_{y_i}^{r_i} \sqrt{R^2 - y^2} \cdot \mathrm{d}y\right) \\ S_4 = \pi R^2 - 2\left(\int_{d-R}^{y_i} \sqrt{r_i^2 - (d-y)^2} \cdot \mathrm{d}y + \int_{y_i}^{r_i} \sqrt{R^2 - y^2} \cdot \mathrm{d}y\right) \\ y_i = \frac{R^2 + d^2 - r_i^2}{2d} \\ y_o = \frac{R^2 + d^2 - r_o^2}{2d} \end{cases}. \tag{11}$$

Relations between the field angle and K_a of annular obscuration with different r_i and r_o are shown in Fig. 7. The effect of annular obscuration is to adjust the K_a of the oblique field between paraxial and marginal. The greater the r_i is, the greater the field angle of minimum K_a will be. The greater the difference between r_i and r_o is, the smaller the minimum K_a will be. Synthesizing the results in Figs. 5 and 7, we can now deduce that the K_a can be changed optionally by a designed series of circular and annular

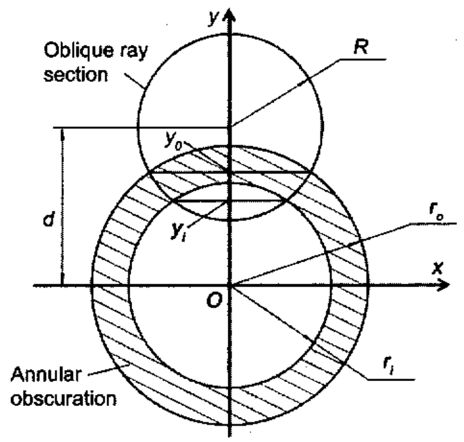

Fig. 6. Relation of oblique ray section and annular obscuration.

obscurations assembled in the optical system. Therefore, the lens' relative illumination distribution is also adjustable to make illumination of image plane uniform.

The obscurations to optimize illumination uniformity block rays especially in paraxial fields. Therefore, the absolute illumination on the detector is reduced, which may increase some measuring noise. The power of incident laser usually can be changed in PSD sensing applications, so the influence of noise on measuring accuracy can be easily avoided by increasing the power of incident laser.

4. Optimizing by ZEMAX MATLAB DDE

A. Description

For an optical system design, calculation of the image plane's relative illumination is done in optical design software by ray tracing. To realize optimization of illumination uniformity by obscurations in this paper, a large amount of ray tracing is needed, so automated optimization in a computer program is considered.

The optical design software ZEMAX offers a dynamic data exchange (DDE) protocol based on the Windows operating system between programs [12]. By an established DDE link, MATLAB can act as client program and request data from ZEMAX. Theoretically, any complex optimizations can be automatically executed. In our optimization, positions and sizes of circular and annular obscurations are set to be variables. Then, because relative illumination is given by ZEMAX, we define the illumination uniformity as the ratio of minimum to maximum illumination on the image plane and set this ratio to be the merit function.

B. Result

Illumination uniformity optimization is done in the PSD sensing optical system described in Section 2. First, we add a circular obscuration into the system. Because the tentative computing shows the position of this circular obscuration is not very sensitive near the first lens, the first lens' presurface is taken as the circular obscuration's position in order to simplify the fabrication. We can make the obscuration by painting black paint on the lens directly to avoid adding a new plane plates. The radius of circular obscuration r is optimized by MATLAB linked to ZEMAX. The lens has the maximum illumination ratio when $r = 6.63$ mm. The illumination uniformity is enhanced to 38.8% from the original 12%. Relative illumination optimized by circular obscuration is shown in Fig. 8.

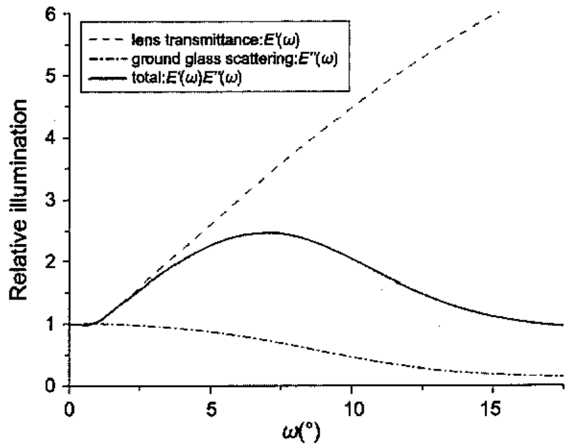

Fig. 8. (Color online) Relative illumination optimized by circular obscuration.

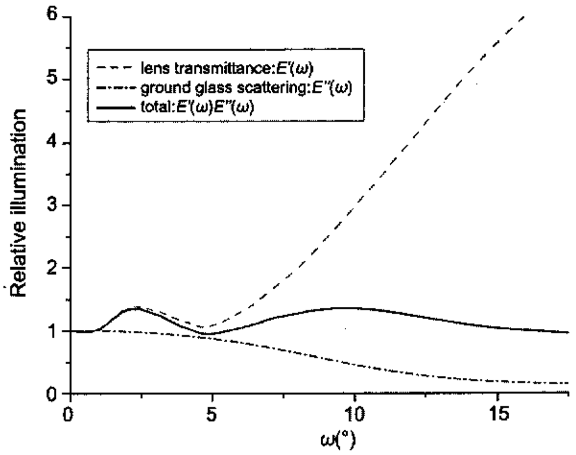

Fig. 9. (Color online) Relative illumination optimized by compounds of circular and annular obscuration.

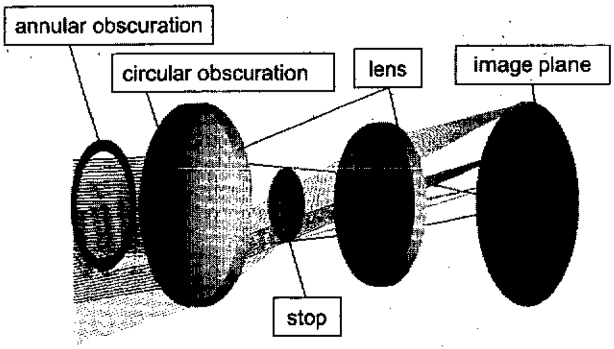

Fig. 10. (Color online) 3D layout of optimized optical system.

Second, an annular obscuration is added to do further optimization. It shows that the maximum illumination of the lens occurred in the 7.5° field and it needs adjustment by annular obscuration. There are three variables: the distance between annular obscuration and the first lens' presurface l, the inner radius r_i, and the outer radius r_o of annular obscuration. By computing, the optimized values of these three variables are $l = 10.32$ mm, $r_i = 7.87$, and $r_o = 9.59$. Relative illumination after the two-step optimization is shown in Fig. 9. Now the illumination uniformity on the PSD has been improved to 69.7%. It is about 5.8 times, compared with original system. The requirement for accurate PSD sensing is satisfied. The three-dimensional (3D) layout of final optical system is shown in Fig. 10.

5. Summary

Illumination nonuniformity on an image plane in a PSD sensing optical system is harmful to its sensing accuracy. The method using obscurations to optimize illumination by adjusting ratios of the oblique ray section to the paraxial ray section is realized in this paper. Compared with general methods, this method is simple and efficient. In the example, the illumination uniformity is increased from 12% to 69.7%. Because almost all of the refractive wide field optical systems' illumination is symmetrical axially, the method used in this paper can be an optional solution to optimize illumination uniformity in many other applications.

References

1. J. Lei, J. Fu, and Q. Guo, "Correction of uneven illumination on gun bore image," Laser Optoelectron. Prog. **48**, 061002 (2011).
2. L. Wang, G. He, and X. Shen, "A system for examining the image planes' illumination nonuniformity of image-forming system on photoelectric measuring equipment using CCD," Optoelectron. Devices Technol. **28**, 212–215 (2008).
3. http://www.schneiderkreuznach.com/pdf/foto/centerfilter.pdf.
4. R. M. Sales, S. Chakmakjian, D. J. Schertler, and G. M. Morris, "LED illumination control and color mixing with engineered diffusers," Proc. SPIE **5530**, 133–140 (2004).
5. http://www.opto-engineering.com/telecentric-lenses-tutorial.html.

6. S. Salvatori, G. Mazzeo, and G. R. Conte, "Voltage division position sensitive detectors based on photoconductive materials part II: device performances and experimental results," IEEE Sens. J. **8**, 218–224 (2008).
7. A. Mäkynen, J. Kostamovaara, and R. Myllylä, "Positioning resolution of the position-sensitive detectors in high background illumination," IEEE Trans. Instrum. Meas. **45**, 324–326 (1996).
8. J. H. G. Huisstede and B. D. van Rooijen, "Dependence of silicon position-detector bandwidth on wavelength, power, and bias," Opt. Lett. **31**, 610–612 (2006).
9. A. Lu, H. Yuan, and A. He, "Experimental study of the effect of light source on position precision of PSD," Opt. Laser Technol. **24**, 192–195 (2000).
10. Y. Wang, *Fish-Eye Lens Optics* (Science, 2006), pp. 61–64.
11. S. T. Yang, R. L. Hsieh, Y. H. Lee, and R. F. W. Pease, "Effect of central obscuration on image formation in projection lithography," Proc. SPIE **1264**, 477–485 (1990).
12. *ZEMAX Optical Design Program User's Guide* (ZEMAX Development, 2009), p. 715.