Hollow conic beam generator using a cylindrical rod and its performances

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Abstract. By numerical simulations, it has been shown that a conventional cylindrical rod can be used as a hollow conic beam generator by illuminating a parallel laser beam inclined to the axis of the rod. Half of the conic beam is formed by the reflection at the surface of the cylindrical rod, and the opposite side of the conic beam by its transmission. We discuss the parameters to determine the size of the conic beam and the effect of the dielectric multilayer coating on the intensity distribution of the conic beam. The line beams of the shapes such as circle, ellipse, parabola, or hyperbola can be generated by this hollow conic beam generator, depending on the position and orientation of the observing plane.
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1 Introduction

An optical element determines the scope at which light can be controlled. Since antiquity, people have used optical elements to focus light at a point or to change the direction of propagation of the light.[1] As a result, many optical elements have been developed, such as lenses, mirrors, prisms, beamsplitters, and so on. However, the kind of optical element is still restricted. By the known optical elements, we are limited to freely control the light in the shape or size that we want. It is important to develop a new optical element, since the advent of a new optical element would provide a new degree of freedom in optical science and technology. Recently, we have reported a *hollow tube prism*, an optical element that diffuses the 1-D laser beam into an omnidirectional plane beam.[2–4] The *hollow tube prism* provides a level of 360-deg reference plane for marking an area or aligning objects in a vertical or horizontal line. As a type of 2-D beam, it is possible to consider a hollow conic beam. According to the geometry, it is known that the cross section of the cone can be a circle, ellipse, parabola, or hyperbola, depending on the position and orientation of the observing plane. These line beams with various shapes can be generated by the hollow conic beam generator. However, there has been no single and simple optical element to generate a hollow conic beam. Instead of a single optical element, a scanning mirror inclined to the axis of rotation is used to generate a conic beam.[5,6] Axicon optics or the circular refraction of biaxial crystal have been also used as another method to generate a conic beam.[7–9]

In this work, we report a simple optical element to generate a hollow conic beam. As shown in Fig. 1(a), the structural model indicates that a conventional cylindrical rod can be used as a hollow conic beam generator by illuminating a parallel laser beam inclined to the axis of the rod.[10] Half of the conic beam is formed by the reflection at the surface of the cylindrical rod, and the opposite side of the conic beam by its transmission. The apex angle of the conic beam is controlled by just changing the angle θ between the ray axis of the laser beam and the axis of the cylindrical rod. The thickness and radius of the hollow conic beam is determined by the beam size of the source and the angle θ, respectively. When the observing plane is perpendicular to the axis of the cylindrical rod, the thickness and radius of the circular beam is calculated by the formula as (beam size of source)/cos θ and (distance from source to screen) $\times$tan θ, according to the geometry. Compared with the previous methods for generating a hollow conic beam, our hollow conic beam generator has many advantages in cost, structure, and stability.[10]

2 Geometry Used in Simulation

Our theoretical study on a hollow conic beam generator has been based on ray tracing by the optical design software, *LightTools*®, Version 4.0 (Optical Research Associates,

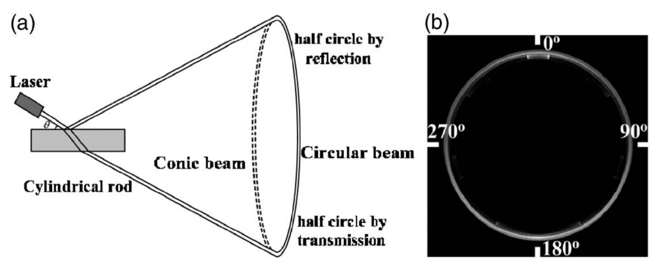

Fig. 1 (a) Schematic diagram of the hollow conic beam generator. A conventional cylindrical rod is used as a hollow conic beam generator by illuminating a laser beam inclined to the axis of the rod. Half of the conic beam is formed by the reflection at the surface of the cylindrical rod, and the opposite side of the conic beam by its transmission. The angle θ represents the angle between the ray axis of the laser beam and the axis of the cylindrical rod. (b) Scattered pattern of the hollow conic beam on the observing plane perpendicular to the axis of the cylindrical rod.

Pasadena, California). Here, a cylindrical rod 3.0 mm in diameter was used as a hollow conic beam generator. BK7 from Schott was assumed as the material and the wavelength was 632.8 nm. It was considered that a laser source has a uniform beam profile of square shape. We used a square rather than a circle as the shape of the source to illuminate entirely and uniformly one side of the cylindrical rod. And we used the uniform beam profile rather than the Gaussian beam profile to increase the uniformity of the intensity distribution of the conic beam. The effect of the beam profile on the intensity distribution is discussed in the next section. In reality, this uniform beam of square shape can be generated by using a beam expander and a square aperture. In simulation, we considered a number of rays across the diameter of a cylindrical rod. The source was modeled by 100,000 parallel rays with a square size of 3.0×3.0 mm. The angle θ between the ray axis of the laser beam and the axis of the cylindrical rod was 20 deg. The observing plane was placed at a distance of 205 mm from the source and had the square size of 180×180 mm and the uniform grid 300×300.

By tracing the transmission and reflection of rays at the surface of the cylindrical rod, we obtained the irradiance $I(i,j)$ at the i'th grid on the horizontal axis and j'th grid on the vertical axis of the observing plane by counting the number of rays per unit area. This work was performed by using the raster chart option of *LightTools*®. Figure 1(b) shows the scatter pattern of the conic beam on the observing plane. It represents a circular beam, because the observing plane is perpendicular to the axis of the cylindrical rod. To analyze the beam pattern, we have assigned the angles at the circular beam, as shown in Fig. 1(b). The half circular beam from 90 to 270 deg is generated by the transmitted light at the cylindrical rod and the opposite half circular beam by the reflected light. These half circular beams are well matched to each other to generate an entire circular beam. In Fig. 1(b), the strange patterns around 0 and 180 deg inward of the circular beam come from the multireflections at the surfaces of the cylindrical rod. This multireflection pattern can be removed by cutting properly the cylindrical rod or rapping it by an absorber. The thickness of the circular beam was obtained as 3.19 mm from the previously mentioned formula, and the value was confirmed by the simulation.

3 Intensity Distribution

For a practical application of a hollow conic beam generator, it is desirable that the intensity distribution of the light is uniform over all angles. By numerical simulations on various hollow conic beam generators and experiences from the study of a *hollow tube prism*, we have found that the reflectance at the surface is the primary factor that determines the uniformity of the intensity distribution.[2] We have considered the proper dielectric multilayer coating on the surface of a cylindrical rod. Figure 2(a) shows the reflectances of the s and p polarizations on the surfaces of various coated cylindrical rods. For these coatings, we have performed ray tracings and obtained the scattered patterns on the observing plane. The intensity distribution of the light versus an angle is calculated by counting the number of rays corresponding to the range of a particular angle. The coordinate of the angle is the same with that of Fig. 1(b).

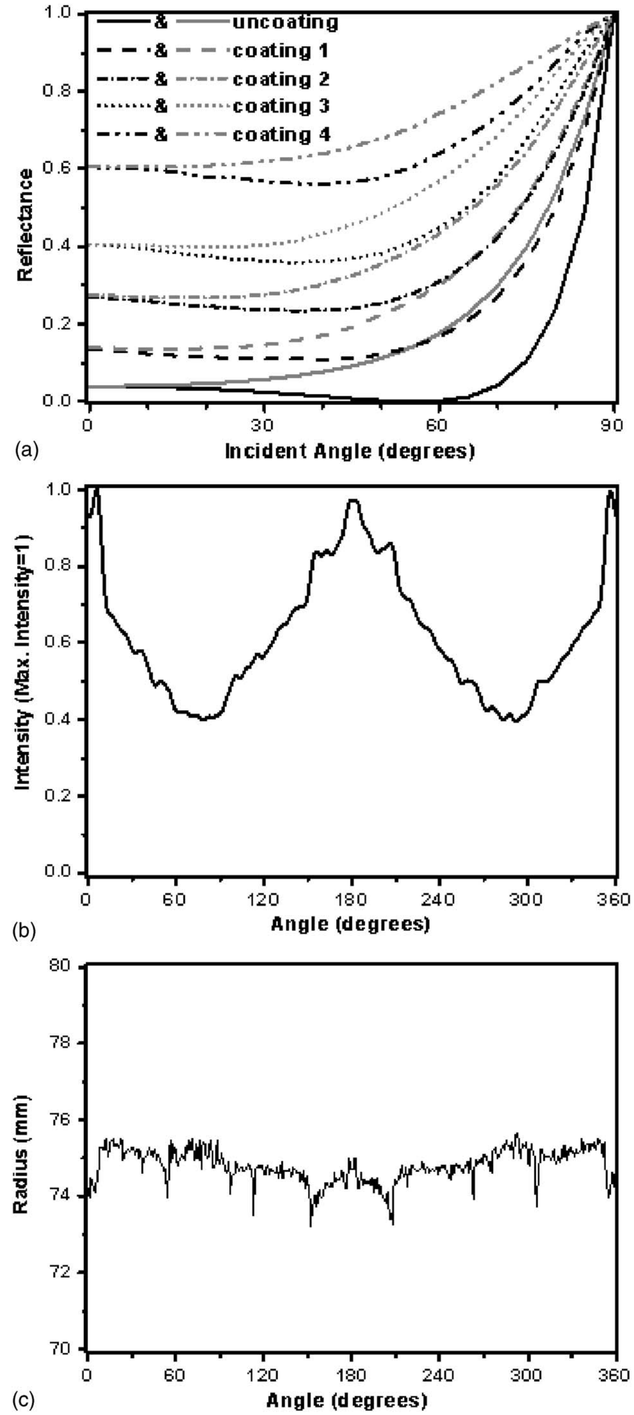

Fig. 2 (a) Reflectances at the surface of the uncoated and various multilayered cylindrical rod. In this graph, the black line represents the reflectance of the p polarization and the gray line represents the reflectance of the s polarization. (b) A typical intensity distribution versus an angle of the circular beam, generated by the hollow conic beam generator with coating 1. The maximum intensity is set as 1. (c) The radius versus an angle of the circular beam, generated by the hollow conic beam generator with coating 1.

For an uncoated cylindrical rod, the incident rays mostly propagate into the range of 90 to 270 deg because of low reflectivity. As the reflectance increases, the number of rays corresponding to the ranges of 0 to 90 deg and 270 to

Table 1 Statistics of the intensity distribution versus an angle of the circular beam, generated by the hollow conic beam generator with various coating designs. Here, the contrast is defined by $(I_{max} - I_{min})/(I_{max}+I_{min})$, where I_{max} and I_{min} are the maximum and minimum intensities, respectively.

	Mean	Standard deviation	Minimum value	Contrast
Uncoated	0.543	0.254	0.267	0.578
Coating 1	0.620	0.170	0.395	0.434
Coating 2	0.489	0.125	0.368	0.462
Coating 3	0.502	0.140	0.343	0.489
Coating 4	0.536	0.193	0.243	0.609

360 deg increases. The uniformity of the intensity distribution is evaluated by calculating the mean value, the standard deviation, the minimum value, and the contrast when the maximum intensity is set as 1. The results are summarized in Table 1. Here, the contrast is defined by $(I_{max} - I_{min})/(I_{max}+I_{min})$, where I_{max} and I_{min} are the maximum and minimum intensities, respectively. Among the coating specifications of Fig. 2(a), coating 1 results in the largest minimum value, while coating 2 results in the smallest standard deviation, as shown in Table 1. The minimum value of the intensity is a more important factor than the standard deviation in the application of a hollow conic beam generator, because the minimum value determines the performance. Therefore, we have selected the cylindrical rod with coating 1 as the coated hollow conic beam generator for the apex angle of 20 deg. The hollow conic beam generator with coating 1 has the contrast of 0.434, and this value represents that I_{max} is 2.53 times stronger than I_{min}.

The human eye's perception for brightness depends on each individual person. And there is no exact psychophysical theory to present quantitatively the perception for brightness and a threshold value. Fechner's law describes only qualitatively that brightness perceived by the human visual system is a logarithmic function of the light intensity incident on the eye.[11] The hollow conic beam generator with coating 1 has a contrast of 0.434, and this value represents that the maximum intensity is 2.53 times stronger than the minimum intensity. If the laser source has enough intensity, we expect that this difference between the maximum intensity and the minimum intensity is trivial, and the intensity distribution of the conic beam is good enough for some practical applications of the hollow conic beam generator such as displaying applications, laser security systems, etc., as well as scientific tools.

Next, we discuss the quality of the conic beam generated by the cylindrical rod with coating 1. Figure 2(b) shows the intensity distribution versus an angle of the hollow conic beam generator. As mentioned before, the half circular beam from 90 to 270 deg is generated by the transmitted light at the cylindrical rod, and the half circular beam from 0 to 90 deg and from 270 to 360 deg by the reflected light. For coating 1, the transmission and reflection are balanced. However, the ranges of 60 to 90 deg and 270 to 300 deg show low intensity distributions compared with that of 0 or 180 deg, so that it gives us the contrast of 0.434. If the input beam has a Gaussian profile, the contrast will be greater than 0.434 because the light intensity from 60 to 120 deg or from 240 to 300 deg depends on the amount of the ray incident on the edge of the cylindrical rod.

As another factor to determine the quality of the conic beam, we have checked whether the circular beam generated by the hollow conic beam generator looked like a perfect circle. The radius of the circular beam versus an angle is calculated by averaging the positions of rays corresponding to the range of a particular angle. Figure 2(c) shows the result of the hollow conic beam generator with coating 1. The radius has the mean value and standard deviation of 74.8 and 0.44 mm, respectively, and fluctuates between 73.2 and 75.7 mm. It has an error of plus or minus about 1.5 percentage points. In Fig. 2(c), the dips around 0, 150, 210, and 360 deg occur due to the multireflection at the surfaces of the cylindrical rod. We expect that this error of the radius is negligible during application, considering that the thickness of the circular beam is 3.19 mm. The nonsmooth profile of Fig. 2(c) is due to the finite number of incident rays in simulation.

4 Conclusions

We report a simple scheme to generate a conic beam by using a conventional glass rod with proper dielectric multilayer coating. We expect that the application area of the hollow conic beam generator is very broad in various fields of science and technology. The line beams with various shapes such as circles, ellipses, parabola, or hyperbola can be generated by the hollow conic beam generator, and the size of the conic beam is controlled by simply changing the angle between the laser beam and the axis of the cylindrical rod. Moreover, the hollow conic beam generator can be used as a security system that screens the valuables from the invader.

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