Design of an Integrating Sphere as a Uniform Illumination Source

Alfred Ducharme, Arnold Daniels, Eric Grann, and Glenn Boreman, *Member, IEEE*

***Abstract*—The design and fabrication of an integrating sphere to provide a uniform illumination source was the basis for a student laboratory project. The design process emphasizes several important concepts in radiometry. An integrating sphere is a useful component for other student laboratory experiments, and the design presented is cost-effective when compared with commercially available products.**

***Index Terms*— Integrating sphere, optics, optoelectronics, radiometry.**

I. INTRODUCTION

INTEGRATING spheres are used in many applications to provide a uniform source of optical radiation. The basic configuration is straightforward, that of a sphere coated on the inside surface with a diffuse-reflecting material. Entrance and exit apertures provide a means for introducing and extracting the flux, and any radiation that enters is generally reflected many times before it exits. The main design goals are uniformity of radiance ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$) across the output port and throughput (ratio of output to input flux).

Commercially available spheres have excellent uniformity (99%) and throughput (70%), but their cost, approximately $9000 for a 50.8-cm-diameter sphere with a 20.32-cm-diameter exit port [1], can be a drawback for student-laboratory applications, particulary those which require a large-area output aperture. The sphere design presented in this paper was fabricated for less than $300, and had a uniformity of 98.5%, over a 15.24-cm-diameter output aperture. The measured throughput of our sphere was 12%, limited primarily by the relatively low reflectance of the interior coating.

Section II describes the design process for the integrating sphere. Section III gives pertinent details of the fabrication. Section IV outlines the testing and optimization procedures.

II. DESIGN PROCESS

Our overall design goal was to have a source that would uniformly illuminate a square transparency of area (10.16 cm)^2. These transparencies are used in resolution testing of optical systems [2], and the uniformity of the target illumination is important to the accuracy of the resolution measurement. The aperture diameter used was 15.24 cm to ensure that the square transparency would be inscribed within the circular exit aperture. The radiance uniformity across the output aperture is best when the entrance and exit apertures comprise a small fraction of the surface area of the sphere. An approximate design rule [3] for assuring uniformity is to restrict the exit-port area to less than 5% of the total surface area of the inner surface of the integrating sphere. Approximating the area of the circular cap removed by a flat disc, this constraint can be expressed as

$$\frac{A_{\text{exit port}}}{A_{\text{sphere}}} = \frac{\pi r^2}{4\pi R^2} \leq 0.05 \tag{1}$$

where r is the radius of the exit port and R is the radius of the integrating sphere. Using (1) we determined that our integrating sphere needed a diameter $2R \geq 34.29$ cm. Exceeding this diameter will only improve the uniformity at the exit port so we decided to use a diameter $2R = 40.64$ cm.

The next design consideration was to determine the best method for introducing flux into the sphere. This decision is guided by the following factors. The radiance at the exit port is directly related to the radiance on the opposite wall of the sphere. Thus, this region needs to be uniformly illuminated by the input flux. Emperically we found that the best output uniformity is achieved when the input source is diffused as it enters the main sphere. The input flux must be diffusely reflected several times before exiting the sphere to assure uniformity. This condition requires that the input ports should not be directly observable from any position in the exit port.

Considering these factors we used two 15.24-cm-diameter satellite spheres for introduction of flux into the main sphere, as seen in Fig. 1. Each sphere had a 5.08-cm-diameter exit aperture, joined to a matched input aperture on each side of the main sphere. An opal-glass diffuser was placed between the two satellite spheres and the main sphere further diffuse the input flux being introduced into the main sphere. To produce uniform illumination of the wall opposite the exit port, both opal-glass diffusers had their normals pointed into the rear hemisphere as much as possible within the additional design constraint that the satellite spheres not be allowed to protrude past the rim of the exit port. To eliminate the direct ray paths between the satellite-sphere diffusers and the exit port we installed opaque baffles to cover the field of view (FOV) between the input ports and the exit port. The placement of

---

Manuscript received May 23, 1994. This work was performed when the authors were with the Department of Electrical Engineering, Center for Research and Education in Optics and Lasers, University of Central Florida, Orlando, FL 32816 USA.

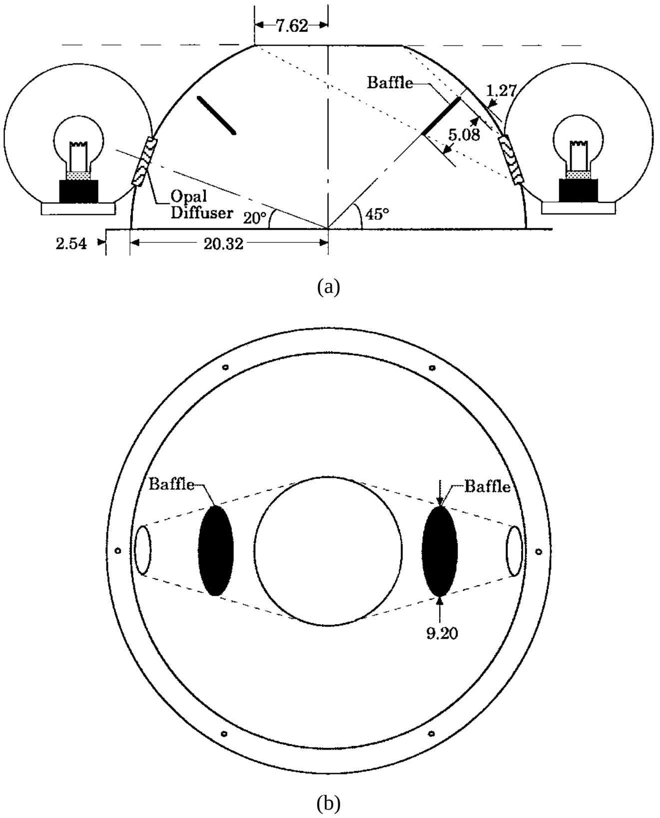
A. Ducharme is with Visidyne Inc., Burlington MA 01803 USA.

A. Daniels is with Pacific Sierra Research Corporation, Santa Monica, CA 90405 USA.

E. Grann is with Oak Ridge National Laboratory, Oak Ridge, TN 37932 USA.

G. Bereman is with the Department of Electrical Engineering, Center for Research and Education in Optics and Lasers, University of Central Florida, Orlando, FL 32816 USA.

Publisher Item Identifier S 0018-9359(97)03328-1.



(a)

(b)

Fig. 1. Design drawing for the integrating sphere, indicating baffle positions and source hemispheres. Dimensions in centimeters. (a) Side view, (b) Top view.

the baffles is determined by two design constraints. The baffles should not be visible to an observer looking into the sphere through the exit port. Also, the baffles should be placed far enough away from the input ports so that they do not impede the flux from entering the main sphere. In this design, we placed the baffles at a 45° angle from the bisector plane of the hemisphere. At this angle, the FOV lines determine that our baffles should be 9.21-cm by 5.08-cm ellipses.

The diffuse-reflecting coating on the inner surface of the sphere has a large impact on the flux-transfer efficiency of the sphere, because the flux experiences a large number of reflections, and any absorption loss is suffered many times in succession. The throughput (τ) of the sphere is defined as the ratio of the flux exiting the sphere to the input flux provided by the source spheres. This can be calculated theoretically [3] using

$$\tau = \frac{\phi_e}{\phi_i} = \frac{\rho f_e}{1 - \rho(1 - f_j)} \tag{2}$$

where ρ is the reflectance (the ratio of reflected power to incident power) of the sphere wall, f_e is the area of the exit port divided by the surface area of the sphere, and f_j is the area of all ports divided by the surface area of the sphere. Commercially available integrating spheres use diffuse materials such as Spectralon® which has a reflectance of 98.5%. We characterized our candidate surface coatings in terms of their bidirectional-reflectance-distribution function (BRDF), defined [4] as the ratio of the reflected radiance L ($\mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$) to the incident irradiance E ($\mathrm{W \cdot cm^{-2}}$)

$$\text{BRDF} = \frac{L_{\text{reflected}}}{E_{\text{incident}}}. \tag{3}$$

For a Lambertian surface, radiance is not a function of angle, and is equal to [5] the exitance M ($\mathrm{W \cdot cm^{-2}}$) divided by π. For a lossless surface, the reflected exitance equals the incident irradiance. Thus for a lossless Lambertian surface the BRDF $= 1/\pi$. For nonideal surfaces, integration of the BRDF over angle of reflection (from $-\pi/2$ to $\pi/2$) yields the reflectance.

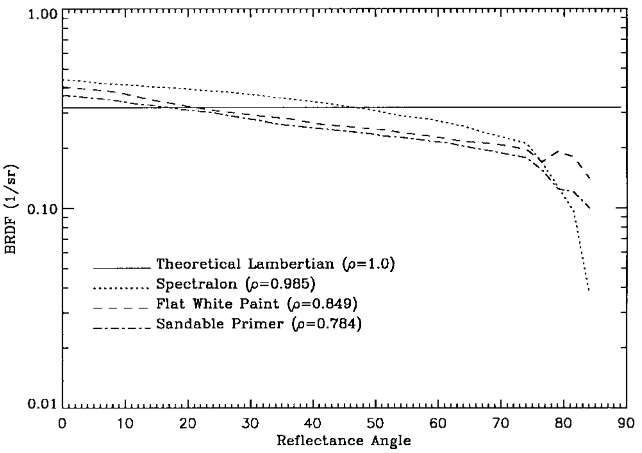


Fig. 2. BRDF curves and resulting reflectances for lossless Lambertian surface, Spectralon surface, and two different paints.

The BRDF was measured with a small photodetector constrained to move on a semicircle, with the diffuse surface illuminated by a HeNe laser beam at near normal incidence. Fig. 2 shows measured BRDF curves for two types of spray paint: a sandable white primer (Krylon), a flat white paint (Krylon), along with the measured BRDF for Spectralon, and the theoretical BRDF curve for a lossless Lambertian surface. The flat white paint had a reflectance of 84.9%, higher than that of the sandable white primer, which had a reflectance of 78.4%. In addition to its higher reflectance, the flat white paint adhered more easily to the acrylic sphere material, so we used it for the interior coating of the sphere.

III. FABRICATION

In this section we describe how each portion of our design was realized. We wanted to limit the cost of the entire sphere to \$300, so most of the materials were purchased from a local hardware store. It was difficult to find a 40.64-cm-diameter sphere so we had one fabricated from 4.76-mm-thick black acrylic at a local plastic fabricator for \$180. For the two source spheres we used outdoor light globes of 15.24-cm diameter. We used a 100-W halogen bulb in each sphere, wired in parallel and attached to a variable voltage source to control the output radiance.

We next painted the internal surfaces of the source spheres and the main sphere. Before painting, all surfaces were sanded so that the paint would adhere properly to the acrylic. The surface uniformity was enhanced by sanding it with fine grit sandpaper after the paint was fully dry. The source spheres

---

® Registered trademark of Labsphere Inc., North Sutton, NH.

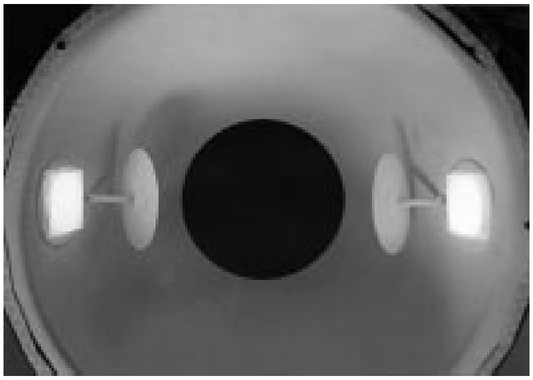


Fig. 3. Details of baffle and diffuser mounting.

were coupled to the main sphere by 5.08-cm-diameter input ports. Opal-glass diffusers were attached inside of the main sphere to cover each port. The baffles for the main sphere were constructed from 1.59-mm-thick lexan plastic. Details of the entrance ports and baffles are seen in Fig. 3. Finally, the outside of all three spheres were painted black to reduce stray light. Foam tape was used as a gasket between the spheres to eliminate light leakage along the seam.

IV. TESTING

For our application the most important performance issue was the uniformity of the radiance across the exit port. We characterized uniformity in terms of the rms variation of radiance (σ_L) around the mean radiance $\langle L \rangle$

$$U = 100\left(\frac{\langle L \rangle - \sigma_L}{\langle L \rangle + \sigma_L}\right). \quad (4)$$

The uniformity was measured by acquiring an image of the output port on a solid-state detector-array camera. The mean and standard deviation were then calculated for all pixels within the exit port. For our design the measured uniformity was 98.5%, using (4). In addition to a purely numerical description, a graphical representation of uniformity is valuable for diagnosis of the sphere performance. Fig. 4 shows also a map of the relative radiance, which uses the same image data used for the uniformity measurement, resampled to form a 9-by-11-pixel image. The resampling operation forms an average from a 16-by-16-pixel area in the original image and represents the result as a single pixel. The resampled image data are normalized to the on-axis value. Radiance mappings were used to fine-tune the uniformity of the completed sphere. Once the sphere was placed in the measurement setup, an initial image was obtained for the radiance across the exit port. From this image we were able to determine if the coating was applied evenly. The baffle orientations were also adjusted to achieve the most uniform mapping.

Using (2) we find that the theoretical throughput should be 16%, considering the port areas and the coating reflectance. An experiment was performed to determine the actual throughput for the completed sphere. Throughput is defined as the flux emitted from the exit port divided by the flux input from the source spheres. To measure flux, we placed a large-area photodetector at the image plane of an imaging lens. The flux emitted by both the exit port and the entrance ports (including the diffusers) was measured by focusing the respective port image onto the detector surface. The magnification of the imaging system was adjusted so that the image of the port was contained well within the detector's active area. The measurements were made with the ports at the same distance from the lens, resulting in the same magnification, image distance, and focal ratio $(F/\#)$. Thus the measured flux values have the same ratio as the actual port radiances. In this manner, the throughput was measured to be 12%.

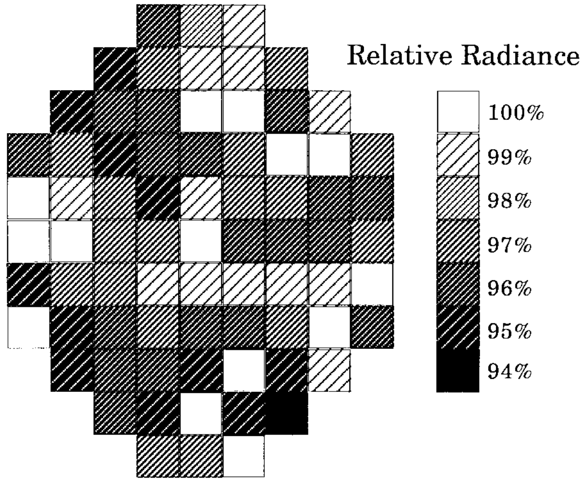


Fig. 4. Radiance uniformity map across the output port.

These values are considerably lower than the 70% theoretical throughput for a comparable commercially available sphere. This difference in thoughput is a result of the difference in reflectance between our coating and the commercial coating, according to (2).

V. CONCLUSION

A student-laboratory project was undertaken to design and fabricate an integrating sphere with uniformity performance being the major design goal. The critical steps in the fabrication process were the positioning of the baffles, and the painting of the inner wall opposite from the exit port.

Our sphere had a measured uniformity of 98.5%, comparable to that obtained in commercially available spheres. The throughput (measured to be 12%) is lower than commercial spheres (typically 70%) because of the absorptive losses in the diffuse coating. This agreed well with the theoretical predictions, given the measured coating reflectance.

The sphere fabrication was completed for under $300 in component costs, whereas commercial spheres of the same uniformity and port size are at least an order of magnitude more expensive. The laboratory project was a vehicle for demonstration of radiometric concepts and measurements to the students, and also resulted in a useful component for other student-laboratory work.

REFERENCES

[1] *Labsphere Price and Ordering Guide*, Labsphere Inc., 1993.

[2] A. Daniels, G. Boreman, A. Ducharme, and E. Sapir, "Random transparency targets for modulation transfer function measurement in the visible and IR," in *Opt. Eng.*, vol. 34, pp. 860–868, 1995.

[3] D. Goebel, “Generalized integrating-sphere theory,” *Appl. Opt.*, vol. 6, no. 1, pp. 125–128, 1967.

[4] J. C. Stover, *Optical Scattering*. New York: McGraw-Hill, 1990, pp. 14–20.

[5] E. Dereniak and G. Boreman, *Infrared Detectors and Systems.* New York: Wiley, 1996, pp. 46-47.

A. Ducharme received the B.S. degree in electrical engineering in 1990 from the University of Massachusetts, Lowell, and the Ph.D. degree, also in electrical engineering, in 1994 from the University of Central Florida, Orlando, where he was a research assistant in the Center for Research and Education in Optics and Lasers (CREOL).

He is presently a Senior Engineer at Visidyne Inc. in Burlington, MA. His current interests are in optical metrology.

Dr. Ducharme received the 1995 Kingslake Medal and Prize from SPIE.

A. Daniels received the B.Sc. degree in electrical engineering in 1984 from the Autonomous University of Mexico, and the B.Sc. degree, also in electrical engineering, from Technion–Israel Institute of Technology, Haifa, Israel, in 1987. He received the M.Sc. degree in electrical engineering from the University of Tel-Aviv, Tel-Aviv, Israel, in 1989, and the Ph.D. degree in electrical engineering in 1994 from the University of Central Florida, Orlando, where he was a Research Assistant in the Center for Research and Education in Optics and Lasers (CREOL).

He is presently a Senior Engineer at Pacific Sierra Research Corporation in Santa Monica, CA. His current interests are in infrared imaging systems.

Dr. Daniels received the 1995 Kingslake Medal and Prize from SPIE.

E. Grann received the B.S. degree in electrical engineering in 1991 from the University of Massachusetts, Lowell, in 1991 and the Ph.D. degree in electrical engineering in 1995 from the University of Central Florida, Orlando, where he was a Research Assistant in the Center for Research and Education in Optics and Lasers (CREOL).

He is presently a member of the research staff in the Instrumentation and Controls Division at Oak Ridge National Laboratory, Oak Ridge, TN. His research interests include diffractive optics, integrated optics, and laser radar. He is the author and coauthor of more than 20 technical publications.

Dr. Grann is a member of OSA and SPIE.

Glenn Boreman (S’80–M’84–M’90) received the B.S. degree from the Institute of Optics, University of Rochester, Rochester, NY, and the Ph.D. degree from the Optical Sciences Center, University of Arizona, Tucson.

He is an Associate Professor of Electrical Engineering in the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida, Orlando. He has held visiting research positions with IT&T, Texas Instruments, U.S. Army Night Vision Laboratory, U.S. Army Redstone Arsenal, and McDonnell Douglas. He has been a Visiting Scholar at Imperial College in London, U.K., and at the Swiss Federal Institute of Technology (ETH) in Zürich. He is author of the optical-transfer-functions chapter in the second edition of the *Handbook of Optics*, and is coauthor of the graduate textbook *Infrared Detectors and Systems* (New York: Wiley, 1996). He has published more than 70 articles in the areas of infrared-detector and focal-plane analysis, optics of random media, infrared-scene projection, and transfer-function techniques.

Dr. Boreman serves the Optical Society of America’s journal *Applied Optics* as the Topical Editor for radiometry and detectors, and is on the Board of Directors of SPIE. He is a Registered Professional Engineer. He received the 1995 Kingslake Medal and Prize from SPIE.