Optical Devices for Turning an Exit Fiber Optic Beam Through 90° Within a Small Region in Space

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P. E. Klingsporn

Published June 1996

Topical Report
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Abstract

The beam emerging from an optical fiber in general diverges quite rapidly within a short distance from the exit face. In applications requiring a fiber beam to be turned through 90° within a region of space much smaller than the fiber can be bent, it is necessary not only to turn the exited beam through 90° , but also to transform it from a diverging beam to one of convergence, particularly when the turned beam is to be received by a second fiber or is required to have a fluence in some plane nearly equal to that within the original fiber. To this end, fiber optic devices for turning an exit fiber beam through 90° in a small region of space were designed on the basis of simple geometric optics. One design involves a combination of a sphere lens and a right-angle prism. Another design utilizes a half-sphere lens with its diametrical face at 45° to the path of the exit fiber beam. Prototype devices of both designs were fabricated, and measurements were made of the transmitted intensity distributions. To better understand the intensity distributions and to provide improved designs, an exact ray tracing analysis was conducted for both right-angle fiber beam turning devices.

Summary

The minimum long-term bend radius of a 400- μm core diameter optical fiber of the type used in DOI (direct optical initiation) development is approximately 75 mm. Applications such as DOI require a right-angle turning of the fiber beam through a much smaller radius. When the beam is allowed to exit the fiber, it diverges quite rapidly with an included angle of 25.4° , as a result of the numerical aperture of 0.22. To turn the diverging exit beam through 90° and deliver it either to another fiber of the same diameter or pass it through a particular region in space at nearly the same fluence it had in the fiber requires an optical device.

In the present work, two right-angle optical devices were investigated for turning an exit fiber beam through 90° . In one arrangement, a sphere lens was used to convert the diverging exit beam into a converging beam and pass it through a right-angle prism to execute the 90° turn. In the other arrangement, a half-sphere lens with its diametrical face inclined at 45° to the axis of the exit fiber beam both provided a converging beam and rotated it through 90° by total internal reflection at the diametrical face. Prototype units of both kinds were fabricated with a half-sphere lens of radius of curvature 1.5 mm in the latter case. In the full-sphere lens/prism arrangements, combinations of a 2-mm diameter sphere lens with a 2.7-mm prism and a 3-mm diameter sphere with a 3.2-mm prism were employed. In all arrangements, the lenses and lens/prisms were mounted on the ends of standard SMA 906 optical connectors with no portion of the devices exceeding the ferrule diameter of the connector. As a result, the exit fiber beams were turned through 90° within a radius of approximately 1.5 mm. Measurements were made of

the transmitted intensity distributions. To aid in beam size measurement, an analysis was made to determine the maximum sensor fiber diameter relative to a hypothetical Gaussian distribution for which the measured distribution would be within a desired percentage of the actual profile.

In the prototype units, simple geometric optics were used to position the full- and half-sphere lenses in relation to the emitting fiber faces of the SMA 906 connectors. Later, ray tracing analyses were conducted for both right-angle designs to take into account the finite size of the emitting fiber face and the fact that, in principle, any point on the emitting face could produce rays at angles as high as allowed by the numerical aperture. It was found for the case of transferring the 90°-turned beam to a fiber of the same diameter as the emitting fiber that the conditions of incident beam diameter and numerical aperture could not both be satisfied completely, simultaneously. The range of variables for the optimum transfer from emitting to receiving fiber were determined from the ray tracing analysis. For applications in which the 90°-turned beam is not transferred to a receiving fiber, and hence the conditions of numerical aperture are not a restraint, it was shown that the turned beam can be delivered to a region in space, where the receiving fiber would otherwise be, at the same or higher fluence as that present in the emitting fiber.

Discussion

Scope and Purpose

Two optical designs were investigated for turning an exit fiber optic beam through 90° . One device uses a combination of a sphere lens and a prism, while the other makes use of a single element in the form of a half-sphere lens. Measurements were made of the transmitted intensities. Ray tracing analyses were done to improve the designs. The overall effort was undertaken to provide a means of turning an exit fiber beam through 90° for those applications in which the right-angle turn must be executed within a small region of space much smaller than is possible by bending the fiber.

Activity

Introduction

The beam emerging from a step-index multimode optical fiber diverges quite rapidly depending on the numerical aperture of the fiber and the extent to which the modes are excited. A lens can be used to provide quasi collimation of the divergent beam emerging from the fiber face. Consequently, one configuration for turning an optical fiber beam through 90° is shown schematically in Figure 1. The lens L_1 is placed at one focal length beyond the emitting fiber face. The collimated beam is turned through 90° either by reflection from a mirror set at 45° in the path or by passage through a right-angle prism as indicated in the figure. A second lens, L_2 , receives the beam reflected from the mirror, or transmitted by the right-angle prism, and brings the beam to focus on the receiving fiber face at one focal length beyond the lens. For coupling from one fiber to another along a straight line, others have used the symmetrical arrangement of a pair of lenses, wherein one lens collimates the output beam of a fiber and the second lens refocuses the expanded beam into a second fiber.¹⁻³ Challans used a "TEE coupling" similar to the arrangement in Figure 1b to divert a portion of the beam in a straight-line expanded beam coupler.⁴

A somewhat simpler arrangement than that in Figure 1 can be used in which only one lens is employed. In this case, the lens is placed such that the emitting and receiving fiber faces are located, respectively, at conjugate object and image distances on either side of the lens. Again, a mirror or prism can be used as indicated in Figure 2a. For this geometry, the lens forms an image of the emitting fiber face on the receiving fiber face. In the case of the arrangement in Figure 2b, total internal reflection occurs at the diametrical face of the half sphere. By symmetry before and after reflection in the plane of Figure 2b, the half sphere has the same focusing action as a full sphere lens along a single axis.

Figure 1. Two Possible Optical Arrangements for Turning an Exit Optical Fiber Beam Through 90° and Coupling It Into a Receiving Fiber. [View (b) uses a mirror while (a) relies on total internal reflection within a prism.]

Figure 2. Two Possible Optical Arrangements for Turning an Exit Beam 90° Using Only One Lens. (A conjugate object-image distance relationship exists between the emitting fiber face and lens and between the lens and the receiving fiber face.)

The geometry of Figure 2 is useful also in situations where it is desired to turn the emitted fiber beam through 90° and illuminate an area that is not necessarily the same as the receiving fiber face. That is, the beam transmitted by the prism or half-sphere is allowed to illuminate an area at some prescribed distance beyond the prism, and no receiving fiber is present.

Sampling a Light Beam With an Optical Fiber

Consider the arrangement shown in Figure 3 in which an optical fiber is to be used as a probe for measuring the intensity distribution in a transverse plane of an axially symmetric beam. Let the beam be Gaussian with an intensity profile represented by the relation

$$I = I_0 e^{-2\left(\frac{R}{A}\right)^2}, \quad (1)$$

where A is the $1/e^2$ beam radius. The fiber is to be moved through the center of the beam, with the fiber axis at all times maintained parallel to the axis of the Gaussian beam. The fiber face intercepts a finite portion of the Gaussian beam and, hence, for any position of the fiber in the beam, the intensity varies over the fiber face. Therefore, the energy transmitted by the fiber represents a complex average over the region intercepted in the beam. What is the maximum diameter of the fiber in relation to the $1/e^2$ beam radius for which the intensity mapping measured with the fiber differs by no more than a prescribed amount from the actual Gaussian beam profile? The Gaussian factor is not integrable over finite limits on R and therefore a numerical summation method must be used to answer this question. The geometry of Figure 4 is useful in performing the analysis to answer this question. Let the fiber of radius r be positioned in the beam with its center at distance l from the center of the Gaussian beam. Consider first the case in which $l > r$, as depicted in Figure 4a. The fiber intercepts a radius in the range $l-r$ to $l+r$ within the beam. Let P be an arbitrary point on the periphery of the fiber. The half-angle θ subtended by this point can be found from the law of cosines through the relation $r^2 = R^2 + l^2 - 2Rl \cos \theta$, which gives

$$\theta = \arccos \left(\frac{R^2 + l^2 - r^2}{2Rl} \right). \quad (2)$$

The arc length at radius R in the beam intercepted by the fiber is $2R\theta$. The intensity at radius R is $I_0 e^{-2(R/A)^2}$ and, hence, the energy intercepted by a region of radial thickness ΔR at radius R is $\Delta E = 2R\theta \Delta R I_0 e^{-2(R/A)^2}$. This provides a method for calculating the energy intercepted by the fiber to within any predetermined level of accuracy.

Figure 3. Sampling a Gaussian Beam Intensity Distribution With a Fiber. [(a) Representation of an axisymmetric Gaussian beam intensity distribution. (b) Schematic of fiber used to sample Gaussian intensity. Fiber is moved in radial direction, with axis parallel to Gaussian symmetry axis.]

Figure 4. Geometry Used in Deriving Equations 2-12 of Text. (In (a) the fiber center is at distance $l > r$ from center of Gaussian beam. In (b), $l \leq r$. R is the distance from Gaussian center and ΔR is a small increment in this distance.)

Let the radial increment ΔR in the Gaussian beam be determined by dividing the fiber diameter into N equal segments to give

$$\Delta R = \frac{2r}{N}. \quad (3)$$

The energy intercepted by the fiber can be written as

$$E = \sum_{n=0}^{N-1} 2R_n \theta_n I_n \Delta R, \quad (4)$$

where

$$\left. \begin{aligned} I_n &= I_0 e^{-2(R_n/\Lambda)^2} \\ \theta_n &= \arccos \left[\frac{R_n^2 + l^2 - r^2}{2R_n l} \right] \\ R_n &= l - r + \left(n + \frac{1}{2} \right) \Delta R. \end{aligned} \right\} \quad (5)$$

For the case in which $l < r$, the geometry in Figure 4b is useful. The fiber face can be divided into two regions, the first of which is a circle of radius $r-l$; and the second is the region exterior to this circle and bounded by the fiber radius. The total energy arriving on the fiber face is then

$$E = E_1 + E_2. \quad (6)$$

The energy E_1 arriving on the circular region of radius $r-l$ on the fiber face is

$$E_1 = \sum_{n=0}^{\frac{N}{2}-1} (2\pi \Delta R_1) R_{1n} I_{1n}, \quad (7)$$

where

$$\left. \begin{aligned} \Delta R_1 &= \frac{r-l}{N/2} \\ R_{1n} &= \left(n + \frac{1}{2}\right) \Delta R_1 \\ I_{1n} &= I_0 e^{-2(R_{1n}/A)^2} \end{aligned} \right\} \quad (8)$$

The radial increment, ΔR_2 , for the calculation of E_2 is

$$\Delta R_2 = \frac{2r - 2(r-l)}{(N/2)} = \frac{4l}{N}. \quad (9)$$

The radius R_{2n} relative to the fiber center for the center of the n^{th} element of radial thickness ΔR_2 is given by

$$R_{2n} = r - l + \left(n + \frac{1}{2}\right) \Delta R_2, \quad (10)$$

and the corresponding half-angle θ_n is found from the law of cosines in Figure 4b. The result is

$$\theta_{2n} = \arccos \left[\frac{r^2 - l^2 - R_{2n}^2}{2lR_{2n}} \right]. \quad (11)$$

Therefore, the energy component E_2 for the case $l < r$ is given by

$$E_2 = \sum_{n=0}^{\frac{N}{2}-1} 2R_{2n} (\pi - \theta_{2n}) I_{2n} \Delta R_2, \quad (12)$$

where $I_{2n} = I_0 e^{-2(R_{2n}/A)^2}$ and R_{2n} , θ_{2n} , and ΔR_2 are given by Equations 9, 10, and 11.

As an example, take the Gaussian $I = I_0 e^{-2(l/A)^2}$ with $A = 1.2/3$ mm corresponding to a $1/e^2$ beam diameter of $3.1/3$ mm. The Gaussian profile I/I_0 as a function of the distance l from the center is given in Table 1, out to a value l such that the intensity in the profile is approximately 3 percent of its value at the center. The expected profile was also calculated, assuming a fiber of diameter $2r = 0.2$ mm is used to sample the Gaussian beam. In the

Table 1. Comparison of Gaussian Intensity Profile With Calculated Profile for Hypothetical Optical-Fiber-Sampling of the Distribution

Distance From Center of *Gaussian (mm)	Gaussian Ratio I/I_0	Calculated Ratio ($E_l/E_{l=0}$) With 0.2-mm Sampling Fiber Diameter **
0	1.0	1.0
0.11	0.9913	0.9914
0.22	0.9657	0.9659
0.33	0.9246	0.9249
0.44	0.8699	0.8703
0.55	0.8043	0.8049
0.66	0.7308	0.7316
0.77	0.6525	0.6536
0.88	0.5726	0.5737
0.99	0.4938	0.4950
1.10	0.4184	0.4198
1.21	0.3484	0.3498
1.32	0.2852	0.2865
1.43	0.2294	0.2306
1.54	0.1813	0.1824
1.65	0.1408	0.1418
1.76	0.1075	0.1083
1.87	0.0806	0.0813
1.98	0.0594	0.0600
2.09	0.0431	0.0435
2.20	0.0307	0.0310

*Gaussian $1/e^2$ radius = 1.667 mm

**Ratio of fiber radius to $1/e^2$ radius = 0.06

calculations, Equations 6 through 12 were used to determine the energy E as a function of l for $l < r$, and Equations 4 and 5 were used for $l \geq r$. The expected measured profile in the form ($E_l/E_{l=0}$), as a function of l , is given in Table 1 alongside the true Gaussian intensity ratio, I/I_0 , for corresponding values of l . It can be seen that the agreement is very good for this case corresponding to the ratio $r/A = 0.06$ of fiber radius r to Gaussian parameter A .

Additional calculations were made. Plots of the percentage difference between the theoretical fiber-measured profile, $(E_f/E_{f=0})$, and the true Gaussian profile, (I/I_0) , as a function of the Gaussian decrease I/I_0 , are shown in Figure 5 for three different values of r/A . For a given value of r/A , the percentage difference increases for increasing distance out from the center of the Gaussian. Note that for a ratio of fiber radius to Gaussian parameter A less than 0.07 the fiber-measured profile agrees with the true Gaussian within one percent or better, out to the $1/e^2$ radius of the Gaussian.

In all the calculations made for the data presented in Table 1 and Figure 5, a value of $N = 500$ was used, corresponding to a partitioning of the Gaussian into 500 segments over the region intercepted by the fiber at each position l . The convergence is fairly fast, however, with respect to N because a value of $N = 400$ gives values of $(E_f/E_{f=0})$ to within one part in 10^5 of the corresponding values for $N = 500$ for all the data of Table 1 and Figure 5.

It is clear from the foregoing that a higher intensity relative to the true Gaussian will be measured as the ratio, r/A , increases beyond the values represented in Figure 5. Figure 6 shows a plot of Gaussian with $A = 0.2$ mm, along with the expected calculated profiles (from Equations 4 through 12) for $r/A = 0.25$, $r/A = 0.4$, and $r/A = 0.5$. For these relatively high values of r/A , it is seen that the measured profiles are 19.5 percent, 53 percent, and 87 percent higher than the true Gaussian, when compared at radial distance corresponding to the $1/e^2$ Gaussian radius. However, it is interesting to note that when the values of A are determined from the fiber-calculated profiles in Figure 6, the agreement is much closer, percentage-wise, to the true Gaussian factor $A = 0.2$ mm. In fact, a plot of the values of A determined from the plots in Figure 6, as a function of the ratio r/A , is given in Figure 7. The maximum deviation in the determination of A occurs at the highest value of r/A , but the percentage is only 13.5 percent.

Prototype Right-Angle Devices

A number of right-angle fiber beam turning devices of the half-sphere lens type and the full-sphere lens/prism combination were built. In each case, a small brass sleeve of outer diameter 0.120 inch with inner diameter machined at 0.085 inch to fit precisely on the stepped-down portion of the standard SMA 906 optical connector was used to position the components in relation to the polished optical fiber face of the SMA 906. For the case of the half-sphere lens, an in-process fixture was built to position the half-sphere with its diametrical face at 45° relative to the axis of the brass sleeve, and a small quantity of EC2216 epoxy was used to bond the half-sphere to the brass. This geometry is shown in Figure 8a. Simple geometric optics were used to calculate the focal length of the half-sphere lens of radius of curvature 1.5 mm, and this was used to determine the length of the brass sleeve for positioning the half-sphere relative to the fiber face so that the fiber face would be imaged in a plane at distance 1 mm beyond the exit portion of the half-sphere. Other sleeves were fabricated with lengths corresponding to focal regions slightly beyond and slightly closer than this value.

Figure 5. Percentage Difference Between Gaussian Profile and Fiber-Calculated Profile (for three different ratios of fiber radius r to Gaussian $1/e^2$ radius A , versus percentage decrease in Gaussian with radial distance from center. The dashed line is percentage decrease (86.47) in Gaussian at $1/e^2$ radius.)

Figure 6. Intensity Ratio $E_l/E_{l=0}$ for Gaussian Profile With $1/e^2$ Radius $A = 0.2$ mm, Versus Radial Distance l , and Fiber-Calculated Profiles for Three Different Ratios of Fiber Radius r to Gaussian Radius A

Figure 7. $1/e^2$ Beam Radius Determined From Fiber-Calculated Profile, Versus Ratio of Fiber Radius r to Gaussian $1/e^2$ Radius A , for $A = 0.2$ mm

The geometry used to secure the full-sphere lens and prism combination on the end of the SMA 906 is shown in Figure 8b. For units with a 2-mm diameter sphere, the sphere lens was inserted in one end of the brass sleeve and secured with epoxy. The internal conical surface served to position the sphere on the axis of the sleeve internal diameter. A right-angle prism 2.7 mm on a side was secured to the outer flat face of the brass sleeve, as shown in Figure 8b. Again, on the basis of simple geometric optics, the sleeve lengths were determined so that the fiber face was imaged on the exit prism face in some units, and slightly before the prism face in other units.

A variation on this geometry was also used in which a 3.0-mm diameter full-sphere lens was combined with a prism 3.2 mm on a side, as indicated in Figure 8c. For this case, the inner diameter of the brass sleeve was made large enough (0.120 inch) to fit precisely over the larger diameter portion of the SMA 906 optical connector.

Figure 8. Prototype Units for Turning an Exit Optical Fiber Beam, From a Standard SMA 906 Connector, Through 90° [(a) geometry of Figure 2b and (b), (c) geometry of Figure 2a]

The full-sphere lenses and the half-sphere lenses were of optical medium LaSF9, with refractive index $n_1 = 1.83$ at the DOI wavelength $\lambda = 1.06 \mu\text{m}$, except for S/Ns 7, 8, 15, 16, and 23-25, which were sapphire with $n_1 = 1.75$ at the same wavelength. The prisms were fused silica with $n_2 = 1.45$ at $\lambda = 1.06 \mu\text{m}$.

The arrangement shown schematically in Figure 9 was used to measure the intensity distribution at the exit prism faces and the exit regions of the half-sphere lens devices. A Hewlett-Packard Model 8153A Lightwave Multimeter was used. The source consisted of a very stable LED with output wavelength at 846 nm. A 10-meter long optical fiber of core diameter $100 \mu\text{m}$ was used to deliver the energy from the source to the input end of each 6-inch long fiber cable of core diameter $400 \mu\text{m}$. The opposite ends of the short $400\text{-}\mu\text{m}$ fibers contained the SMA 906 connectors fitted with the various right-angle fiber beam turning devices described earlier. A fiber of $100\text{-}\mu\text{m}$ core diameter was used as the sensor. The measured diameters of the exit beam in two perpendicular planes are shown in Figure 10, along with the peak measured intensities. The S/Ns 1 through 8 have the 2.0-mm full-sphere lens with a 2.7-mm prism, and S/Ns 9 through 16 have the 3.0-mm full sphere lens with a 3.2-mm prism. S/Ns 17 through 25 are the design with a half-sphere lens of 1.5 mm radius of curvature.

The measurements in Figure 10 were made at the exit prism faces for S/N 1-16 and at the exit portion of the half-sphere for S/N 17-25. The beam diameters at these exit locations are in the range of 0.5 - 0.6 mm. The focusing actions of the full-sphere lens and of the half-sphere lens result in a significantly smaller beam diameter at a distance of 1.5 - 2.0 mm beyond the exit locations. This can be seen from Figure 11 for the half-sphere unit, S/N 17.

The near field distribution of the $100\text{-}\mu\text{m}$ diameter fiber, serving as an input to the 6-inch long $400\text{-}\mu\text{m}$ diameter fiber in Figure 9, was measured using a 10-mm focal-length lens in the arrangement shown in Figure 12a. The ratio of intensity at radial distance out from the fiber center, to the intensity at the fiber center, is given in Figure 13a. The same arrangement of Figure 12a was used to measure the near field intensity distribution at the exit end of the 6-inch long $400\text{-}\mu\text{m}$ diameter fiber, with the input given in Figure 13a. The near field at the exit end of the $400\text{-}\mu\text{m}$ fiber is plotted in Figure 13b.

The far field distribution from the $100\text{-}\mu\text{m}$ diameter fiber serving as an input to the $400\text{-}\mu\text{m}$ fiber in Figure 9, was measured using the arrangement shown diagrammatically in Figure 12b, and the result is plotted in Figure 14a. The results in Figure 14b represent the far field distribution at the exit of the 6-inch long $400\text{-}\mu\text{m}$ diameter fiber segment when the entrance end of the $400\text{-}\mu\text{m}$ fiber is illuminated with the $100\text{-}\mu\text{m}$ fiber.

Text continued on page 24.

Figure 9. Arrangement for Measurement of Peak Energy Received From the Right-Angle Turn Devices Depicted in Figure 8. (For beam size measurement the sensor fiber was moved in the horizontal direction, with its axis always remaining perpendicular to the axis of the 400- μm fiber input to the 90° devices.)

Figure 10. Measured Beam Size and Intensity at Exit Prism Faces and Exit Half-Sphere Regions of Prototype Units of Figure 8

Figure 11. Ratio of Intensity at Distance r' From Center of Exit Beam to Intensity at Center ($r' = 0$), for Observation Plane at Two Distances From Exit Face of Half-Sphere, Prototype S/N 17 of Figure 10.

Figure 12. Optical Arrangements for Measuring the (a) Near Field Intensity Distribution and (b) the Far Field Intensity Distribution From an Optical Fiber Output Face

Figure 13. Near Field Intensity Distributions. [(a) Of the 100- μm fiber face, as input to the 400- μm fiber segment, in the arrangement of Figure 9. The arrangement of Figure 12a was used to make the near field measurement. (b) At the output end of the 400- μm fiber segment in Figure 9. The arrangement of Figure 12a was used after inserting the 400- μm fiber segment at the exit end of the 100- μm fiber.]

Figure 14. Far Field Intensity Distributions. [(a) From 100-μm fiber in arrangement of Figure 9. The optical arrangement of Figure 12b was used to obtain the data. (b) From 400-μm fiber in arrangement of Figure 9. The optical arrangement of Figure 12b was used in obtaining the measurements.]

The multimode step-index optical fiber used in this study has a numerical aperture of 0.22. This is a rather commonly employed value in commercially available specialty fibers, and its significance is that a fiber will receive and transmit rays incident on its end face that make an angle with the perpendicular to the face of $\arcsin(0.22) = 12.7^\circ$, or less. A ray incident at an angle exceeding 12.7° will pass into the cladding of the fiber and fail to be transmitted by the fiber core to the exit end. Therefore, depending on the angular content of the beam that is introduced into one end of a fiber, it is possible under the case of a fully excited distribution for the exit fiber face to emit rays within the entire angular interval 0° to 12.7° at any point on the fiber face. The near field and far field distributions given in Figures 13 and 14 show that the beam used to illuminate the right-angle devices in Figure 8, with the arrangement of Figure 9, does not represent a fully excited fiber beam. However, the beam illuminating the devices does not constitute a point source characterized only by paraxial rays as required by simple geometric optics on which the devices were designed. For example, Figure 13b shows that the intensity at 50% of the fiber radius, $h = 0.10$ mm, is 38% of that at the center of the 400- μm diameter fiber. Figure 14b shows that the angular content of the far field at $\theta = 4^\circ$ is 55% of that at 0° , and the content at $\theta = 8^\circ$ is approximately 20 to 30% of that at $\theta = 0^\circ$. In effect, the fiber beam illuminating the right-angle configurations represents a type of extended source and, therefore, the envelope of rays passing through the right-angle turning devices should be examined by ray tracing as follows.

Ray Tracing

Based on simple geometric optics, and assuming a point source, the spherical aberration is a minimum when the emitting fiber face and the receiving fiber face are located at equal conjugate "object" and "image" distances on either side of the center of the lens.⁵ However, as indicated earlier, the emitting fiber face is not a point source and, furthermore, the rays may make angles as high as 12.7° relative to the axis so that they are incident on the lens at a transverse distance that is a relatively high fraction of the lens radius. For these reasons, ray tracing is required to determine optimum positioning of the emitting and receiving fiber faces.

A detailed ray-tracing analysis was made of the full-sphere lens/prism geometry because it is sufficiently general to allow for determination of the rays arriving at a plane at arbitrary distance beyond the prism. The geometry is shown in Figure 15, and it is assumed that the fiber axis is collinear with a major diameter of the full-sphere spherical lens, and one face of the prism is perpendicular to this axis. Let the fiber of radius r be located at distance, a , from the sphere of radius R , and let the right-angle prism of length L on a side be located at a distance, b , beyond the sphere-lens. The refractive index of the lens is n_1 and that of the prism is n_2 . Consider a ray leaving the fiber face in the plane of the figure at a point on the fiber at distance, h , from the axis,

Figure 15. Combination of Full-Sphere Lens and Prism to Turn Exit Fiber Beam Through 90°. (A general ray path is shown in the plane through sphere center and perpendicular to prism diagonal face. A ray emitted at radial distance h from emitting fiber face center, at angle θ relative to the normal face, eventually arrives at the receiving fiber face, at angle of incidence u , at distance y' from the fiber face center.)

making an angle θ relative to the axis. Consider a plane located at distance, d , beyond the exit prism face, parallel to the prism face. It is shown in the appendix that the ray (h, θ) emerging from the emitting fiber face will intersect the plane at distance y' from the central axis of the exit prism face, where y' is given by

$$y' = [R \cos(2\gamma - \omega_1) - d - R - b] \tan u - R \sin(2\gamma - \omega_1) - L \sin u [n_2^2 - \sin^2 u]^{-\frac{1}{2}} \quad (13)$$

where the angles u , γ , and ω_1 are given by

$$\left. \begin{aligned} u &= 2(\gamma - \omega_1) - \theta \\ \gamma &= \arcsin \left[\frac{\sin(\theta + \omega_1)}{n_1} \right] \\ \omega_1 &= \arctan \left[\frac{x_1 \tan \theta + h}{a + R - x_1} \right] \end{aligned} \right\} \quad (14)$$

and x_1 is the smallest root of the quadratic

$$A x_1^2 + B x_1 + C = 0, \quad (15)$$

where

$$\left. \begin{aligned} A &= 1 + \tan^2 \theta \\ B &= 2[h \tan \theta - a - R] \\ C &= (a + R)^2 + h^2 - R^2. \end{aligned} \right\} \quad (16)$$

The angle u is the angle the ray makes with the axis perpendicular to the exit prism face.

Also, it is shown in the appendix that the angle i_4 , which the ray makes relative to the normal to the prism diagonal face in Figure 15, can be expressed as

$$i_4 = \frac{\pi}{4} - \arcsin \left(\frac{\sin u}{n_2} \right). \quad (17)$$

Therefore, if the prism is surrounded by air of refractive index unity, the condition for total internal reflection at the prism diagonal face is

$$i_4 > \arcsin\left(\frac{1}{n_2}\right). \quad (18)$$

Finally, it is also shown in the appendix that

$$\begin{aligned} y'(-h, -\theta) &= -y'(h, \theta), \\ \text{and} \\ y'(-h, \theta) &= -y'(h, -\theta). \end{aligned} \quad (19)$$

That is, rays emerging symmetrically about the axis of the fiber face in the plane of Figure 15 emerge from the exit prism face with symmetry about the perpendicular to the prism face at its center.

1. Half-Sphere Lens Device

The geometry of the simple half-sphere arrangement for turning the exit fiber beam through 90° is shown schematically in Figure 16. A ray emitted at radius h on the fiber face, at angle θ , enters the half-sphere; and after total internal reflection at the diametrical face, it emerges and arrives at the receiving fiber face, at distance b , at distance y_3 from the center, inclined at angle i_3 . By symmetry in the plane of Figure 16, compared with the full sphere, it can be seen that the angle i_3 and the distance y_3 are both given by the corresponding expressions derived in the appendix. The angle i' that the ray makes with the diametrical face, within the half-sphere, is

$$i' = \omega_1 + \frac{\pi}{4} - \gamma, \quad (20)$$

where ω_1 and γ are given in Equation 14. If the diametrical face is bounded by air, then the condition for total internal reflection at the face is

$$i' > \arcsin\left(\frac{1}{n_1}\right). \quad (21)$$

For the ray tracing analysis, a good starting place is the arrangement in which $a = b$ in Figure 16, which corresponds to equal conjugate object and image distances, and for simple geometric optics with a point source, would give minimum spherical aberration of the rays at the receiving fiber face. The focusing action of the half-sphere lens in the plane of Figure 16 is the same as that of a full-sphere lens of the same radius, and for radius R and refractive index n the focal length is given by $f = nR/2(n-1)$, based on the thick-lens equations of geometric optics.⁶

Figure 16. Geometry of Half-Sphere Arrangement for Turning an Exit Fiber Beam Through 90°.
 (A ray emitted at (h, θ) on the emitting fiber face will arrive at (y_3, i_3) on the receiving fiber face.)

Therefore, for a half-sphere of radius $R = 1.5$ mm, the equal conjugate distance from the sphere center to either fiber face is $2f = nR(n-1) = 3.307$ mm, where the refractive index of the lens medium (LaSF9) is $n = 1.83$. The corresponding distances a and b are $a = b = 2f - R = 1.807$ mm. So to begin, let the receiving fiber face be located at the conjugate distance $b = 1.807$ mm, and let the distance a , representing the emitting fiber face location, be varied to values above and below $a = 1.807$ mm to determine y_3 at which the transmitted rays pass the plane at b , and the corresponding angles i_3 that they make with respect to the normal to this plane. The results are plotted in Figure 17. The two horizontal dashed lines drawn at $y_3 = \pm 0.2$ mm indicate the outer boundaries of the 0.4-mm-diameter receiving fiber. That is, at a given distance a , the transmitted ray will not be intercepted by the receiving fiber face if the value of y_3 (positive or negative) exceeds 0.2 mm (or -0.2 mm). Note that the rays will fall within the range ± 0.2 mm only for values of a in the range $0.767 \text{ mm} \leq a \leq 1.181 \text{ mm}$. If a is not in this range, then the rays will not be intercepted by the receiving fiber face at $b = 1.807$ mm.

A second condition for proper delivery of the rays to the receiving fiber face is related to the numerical aperture. That is, unless the rays incident on the fiber make an angle of $i_3 \leq \arcsin(0.22) = 12.7^\circ$, they will not be transmitted by the receiving fiber. Figure 18 provides a plot of the angle i_3 as a function of the distance a , corresponding to the data of Figure 17. Note that the angle i_3 is equal to or less than 12.7° only if $a \leq 0.723$ mm. This is not compatible with the range of a for which $|y_3| \leq 0.2$ mm and the consequence is that not all of the rays for $0.767 \text{ mm} \leq a \leq 1.181 \text{ mm}$ that are intercepted by the receiving fiber face will be transmitted. From Figures 17 and 18 the two compromising sets of conditions can be summarized as follows for the receiving fiber face located at $b = 1.807$ mm.

Case I: For the emitting fiber face at distance a in the range $0.767 \text{ mm} \leq a \leq 1.181 \text{ mm}$, all transmitted rays will be intercepted by the receiving fiber face, but rays emitted near the periphery ($h = 0.2$ mm) for $\theta > 8^\circ$ have $i_3 > 12.7^\circ$ and hence will not be transmitted by the receiving fiber for distance a near the upper limit of the range.

Case II: For the emitting fiber face at distance $a \leq 0.723$ mm, all rays intercepted at the receiving fiber face will be transmitted by it because the values of i_3 are all less than 12.7° , but at $a \leq 0.723$ mm rays emitted near $h = 0$ with θ close to 12° will not intercept the receiving fiber face.

The condition for total internal reflection in the geometry of Figure 16 is satisfied for all distances a in the range 0.767 mm to 1.181 mm in Figure 17.

Figure 17. Distance y_3 of Rays From Receiving Fiber Face Center, for Constant Distance $b = 1.807$ mm in Figure 16, as a Function of Distance a Between Emitting Fiber and Half-Sphere for Various Emitting Ray Coordinates (h, θ). (The dashed horizontal lines correspond to ± 0.2 -mm boundaries of the 0.4-mm diameter receiving fiber face.)

Figure 18. Incident Angle i_3 of Rays on Receiving Fiber Face, for Constant Distance $b = 1.807$ mm in Figure 16, as a Function of Distance a Between Emitting Fiber and Half-Sphere for Various Emitting Ray Coordinates (h, θ). (The dashed horizontal line corresponds to the numerical aperture condition $i_3 = 12.7^\circ$ for maximum angle of incidence on receiving fiber face for transmission.)

Finally, it should be noted that in an application such as DOI (direct optical initiation) where the turned fiber beam does not need to be coupled into a receiving fiber and the accompanying condition of numerical aperture is not a restriction, then the emitting fiber face distances $a = 0.767$ mm to 1.181 mm all provide a delivery of energy in the plane at $b = 1.807$ mm that fills a circular diameter of 0.4 mm, the same as that of the emitting fiber face, and hence the fluence at distance b is the same as that at the emitting fiber face--minus reflection losses upon entering and exiting the lens.

2. Combination of Full-Sphere Lens and Prism

A sphere lens of diameter 2.0 mm is approximately the smallest commercially available and seemed appropriate for a prototype of this design. As a guide from simple geometric optics, equal conjugate object-image distances give a value of $nR/(n-1) = 2.2048$ mm, for the lens medium (LaSF9) with $n = 1.83$. Hence, the value of a in Figure 15 is $2f-R = 1.2048$ mm, and it follows that a prism with side $L = 1.0$ mm is nearly the largest that can be used for equal conjugate distances because this allows $b \sim 0.1$ mm and $d \sim 0.1$ mm. Prisms with $L > 1.0$ mm are available commercially and so this is a reasonable geometry to begin the ray tracing analysis. Accordingly, the transverse distances y' and corresponding angles u were calculated for distances a ranging from somewhat below to somewhat above the value $a = 1.2048$, and the results are plotted in Figure 19a for representative radial distances h on the emitting fiber face, with limiting values of θ . A plot of corresponding angles of incidence u on the receiving fiber face are given as a function of a and (h, θ) in Figure 20. At $a = 0.67$ mm in Figure 19a the condition for total internal reflection in the prism (see Figure 15) is satisfied except for $h \approx 0$ at $\theta = -5^\circ$ and for $h \leq 0.09$ mm for $\theta = -12.7^\circ$.

Taking into account both positive and negative emitting angles θ over the full range $|\theta| = 12.7^\circ$, the distances y' in Figure 15 were obtained from ray tracing as a function of the distance a to give minimum beam size just beyond the prism exit face. The distance $a = 1.209$ mm was found to achieve this, and the values of y' are plotted in Figure 19b as a function of distance d beyond the prism. Note from the figure that a distance $d = 0.008$ mm gives a minimum beam size of 0.404 mm which is only slightly larger than the emitting fiber diameter of $2|h| = 0.4$ mm.

As in the case of the half-sphere lens, two contrasting sets of conditions are evident, and these are summarized briefly below.

Case I: For the emitting fiber face at distances a in the interval $0.32 \text{ mm} \leq a \leq 1.05 \text{ mm}$, all transmitted rays will be intercepted by the receiving fiber face located at distance $d = 0.1$ mm beyond the prism exit face, but many of the rays emitted at angles θ exceeding 5° , even at low radial distances h , will violate the numerical aperture condition ($u \leq 12.7^\circ$) and hence will not be transmitted by the receiving fiber.

Case II: For the emitting fiber face located at a distance $a \leq 0.187$ mm, all the rays intercepted by the receiving fiber face satisfy the condition of numerical aperture and hence will be transmitted, but at the upper limit of a ($a = 0.187$) rays emitted near the center of the fiber at $h = 0$ and for $\theta > 10^\circ$ will not intercept the receiving fiber because $|y'| = 0.222$ mm, which exceeds the fiber radius 0.2 mm. For increasingly smaller values of a , although the numerical aperture condition is satisfied, fewer and fewer of the rays will intercept the receiving fiber.

Figure 19a. Radial Distance y' of Rays Arriving on Receiving Fiber Face for Full Sphere/Lens Arrangement of Figure 15 as a Function of Distance a Between Emitting Fiber Face and Lens, for Various Emitting Ray Coordinates (h, θ). (The dashed horizontal lines at $y' = \pm 0.2$ mm correspond to the boundaries of the 0.4-mm diameter receiving fiber face.)

Figure 19b. Distance y' of Rays From Receiving Fiber Face Center for Constant Distance $a = 1.209$ mm as a Function of Distance d Beyond Prism Exit Face in the Full-Sphere Lens/Prism Geometry of Figure 15, for Full Range of Positive and Negative Emitting Angle θ . (The dashed horizontal lines at $y' = \pm 0.2$ mm represent the boundaries of a 0.4-mm diameter receiving fiber face.)

Figure 20. Angle of Incidence u on Receiving Fiber Face in the Optical Arrangement of Figure 15 as a Function of Distance a Between Emitting Fiber Face and Lens, for Various Coordinates of Ray Emission (h, θ) on the Emitting Fiber Face. (The dashed horizontal line at $u = 12.7^\circ$ corresponds to the numerical aperture ($NA = 0.22$) of the receiving fiber.)

The results discussed in cases I and II can be summarized more generally with the plots in Figure 21, in which the two dashed curves give the lower and upper limits of the distance a , as a function of the angle θ , for which all rays arriving at the receiving fiber face will be intercepted by the face. For example, for $\theta = 12.7^\circ$, corresponding to the full numerical aperture of the fiber, the distance a must lie in the range 0.32 mm to 1.05 mm, as shown above. However, if only rays emitted at $\theta = 11^\circ$ and less are considered, then a can lie in the range 0.15 mm to 1.17 mm and all rays will intercept the fiber face.

The solid curves in Figure 21 characterize the numerical aperture condition for acceptance of the rays incident on the receiving fiber face. For example, for $\theta = 12.7^\circ$ only those rays emitted at a radius $h \leq 0.17$ mm will be transmitted by the receiving fiber face. If only those rays emitted at angles $\theta \leq 11.5^\circ$ are considered, then all rays emitted out to the periphery of the fiber ($h = r = 0.2$ mm) will be transmitted by the receiving fiber face.

Finally, it should be noted that in those applications such as DOI in which a receiving fiber is not used and the corresponding condition of numerical aperture is absent, the energy arriving at the plane at distance d beyond the exit prism face is contained within a diameter equal to that of the emitting fiber face for the whole range $a = 0.32$ mm to 1.05 mm. Hence, except for reflection losses in traversing the lens and prism, the fluence in the plane at d is the same as that at the emitting fiber face.

3. Half-Sphere Device With $a \equiv b$

For paraxial rays, the results from simple geometric optics indicate that minimum spherical aberration occurs for equal conjugate object/image distances, which corresponds to the emitting and receiving fiber faces being located at distances of 1.807 mm from the nearest faces of the half-sphere lens of radius $R = 1.5$ mm and $n_1 = 1.83$. The ray tracing analysis can be used to determine the optimum, equal distances of the emitting and receiving fiber faces in the configuration of Figure 16. To this end, a plot of y_3 on the receiving fiber as a function of $a \equiv b$ is given in Figure 22a.

Taking into account both positive and negative angles θ over the range $|\theta| = 12.7^\circ$, the distances y_3 in the half-sphere arrangement of Figure 16 were obtained from ray tracing as a function of distance b beyond the exit portion of the sphere for a fixed distance $a = 1.807$ mm. The results are plotted in Figure 22b from which it can be seen that the minimum beam size of 0.44 mm occurs for $b = 1.27$ mm.

Figure 21. Conditions for Interception and Transmission of Rays at Receiving Fiber Face in the Arrangement of Figure 15, With 2-mm Diameter Lens and Right-Angle Prism 1.0 mm on a Side. (The dashed curves give the lower and upper limits on distance a between emitting fiber face and lens, versus ray angle relative to face, for which a ray will be intercepted by the 0.4-mm diameter receiving fiber. The curves designated by various values of h give the radial distance h of a ray emitted by the fiber for which the ray intercepted by the receiving fiber face will be transmitted; i.e., the ray arrives at the receiving face with incident angle $u \leq 12.7^\circ$.)

Figure 22a. Position y_3 of Ray on Receiving Fiber Face, at Distance b from Half-Sphere Arrangement of Figure 16, as a Function of Distance $a \equiv b$ of Emitting Fiber Face From Lens, for Various Coordinates (h, θ) of Emitted Rays. (The dashed horizontal lines at $y_3 = \pm 0.2 \text{ mm}$ correspond to the outer boundary of a 0.4-mm diameter receiving fiber.)

Figure 22b. Distance y_3 of Rays From Receiving Fiber Face Center for Constant Distance $a = 1.807 \text{ mm}$ as a Function of Distance b in the Geometry of Figure 16, for Full Range of Positive and Negative Emitting Angle θ . (The dashed horizontal lines at $y_3 = \pm 0.2 \text{ mm}$ are the boundaries of a 0.4-mm diameter receiving fiber face.)

A plot of the angle of incidence i_3 on the receiving fiber face is given in Figure 23. The compromising conditions for transfer of energy from the emitting fiber to the receiving fiber can be summarized briefly as follows from Figures 22a and 23.

Case I: In order for all rays emitted by a fully excited fiber to be intercepted by the receiving fiber, the distances $a \equiv b$ must lie within the range 1.12 mm to 1.48 mm. However, many of the rays emitted will not be transmitted by the receiving fiber because the numerical aperture is exceeded.

Case II: For $a \equiv b \leq 0.76$ mm, all rays arriving in the plane of the receiving fiber face satisfy the condition of numerical aperture, but many of the rays emitted will fail to intercept the receiving fiber face.

It should be noted that the condition for total internal reflection is satisfied for a in the range 1.12 to 1.48 mm in Figure 22a.

The results in the two cases referred to above can be made more general with the aid of the ray-tracing results given in Figure 24. The two dashed curves in Figure 24 are a plot of the lower and upper limits for $a (= b)$ versus the angle θ at which rays are emitted relative to the emitting fiber face for the case in which all rays arriving at the receiving fiber face will be intercepted by the face. For example, for $\theta = 12.7^\circ$, the limits on a are $a = b = 1.12$ mm to 1.48 mm, in agreement with the results in Figure 22a. If only rays emitted at angles $\theta \leq 9^\circ$, for example, are considered, then Figure 24 indicates that the distance $a = b$ can range from 0.87 mm to 1.61 mm and the rays arriving at the receiving face will all intercept the face.

The solid curves in Figure 24 characterize the numerical aperture conditions for acceptance of the incident rays on the receiving fiber face. For example, for $\theta = 12.7^\circ$, only those rays emitted at a radius $h \leq 0.1$ mm will have an angle of incidence $i_3 \leq 12.7^\circ$ and thereby be transmitted by the receiving fiber. If the angle of emission is $\theta \leq 11^\circ$, then $a = b$ can range from 1.05 mm to 1.54 mm and all the rays will intercept the receiving fiber face, but only those rays emitted at radii $h \leq 0.16$ mm will meet the numerical aperture conditions for transmission by the receiving fiber.

From Figure 24, $\theta = 9.8^\circ$ is the maximum angle of emission on the emitting fiber face for which all the rays with $h \leq 0.2$ mm will not only be intercepted by the receiving fiber face (provided $a = b$ is in the range 0.95 to 1.58 mm), but also will be transmitted per conditions of numerical aperture.

Figure 23. Angle of Incidence i_3 of Rays Arriving at Fiber Face in the Optical Arrangement of Figure 16 as a Function of Distance $a = b$ Between Emitting and Receiving Fibers and Half-Sphere Lens. (The dashed horizontal line at $i_3 = 12.7^\circ$ corresponds to the numerical aperture (NA = 0.22) of the receiving fiber.)

As in preceding cases, it should be noted for this case of a fully excited fiber, if coupling to a receiving fiber is not required, then all emitted rays, for $a = 1.12$ to 1.48 mm, will pass through the plane at b in Figure 16 within a circle of the same diameter (0.4 mm) or smaller, as that of the emitting fiber.

Demagnification of 90-Degree-Turned Beam

The fact that the arrangements of Figures 15 and 16 not only turn the fiber beam through 90° but also have a focusing action makes it possible to demagnify the spot size through which the transmitted energy passes and thereby achieve a higher fluence in the spot than that which exists in the fiber core. The higher fluence as a result of demagnification can be used to offset losses from reflection with uncoated lenses and prism. For an application such as DOI where the turned fiber beam does not need to be coupled into and transmitted by a receiving fiber, the condition of angle of incidence as dictated by the receiving fiber numerical aperture is not a restraint.

Figure 24. Conditions for Interception and Transmission of Rays at Receiving Fiber in the Arrangement of Figure 16, With Half-Sphere Radius $R = 1.5 \text{ mm}$ and $n_1 = 1.83$. (The dashed curves give the lower and upper limits on distance $a = b$ between emitting and receiving fibers and lens, versus the angle of emission θ relative to emitting face, for which rays will be intercepted by the receiving fiber face. The curves designated by various values of h give the radial distance h of an emitted ray for which the ray intercepted at the receiving fiber face will be transmitted; i.e., the ray arriving on the face has incident angle $i_3 \leq 12.7^\circ$.)

The concept of demagnification based on the ratio of image distance to object distance in simple geometric optics can be used as a guide in ray-tracing to achieve a smaller spot size in the plane at distance b in the half-sphere geometry of Figure 16. According to simple geometric optics, if the distance $b + R$ is less than the distance $a + R$, then a demagnification will occur in the plane at b . The actual demagnification was calculated with the aid of the ray tracing equations for a half-sphere of refractive index $n_1 = 1.83$ (optical material LaSF9), with radius of curvature $R = 1.5$ mm, and the results are plotted in Figure 25. The actual demagnification factor M' for spot size in the plane at b is plotted as a function of the simple demagnification factor $M = (b+R)/(a+R)$ for rays emitted for $\theta \leq 5^\circ$. For a distance ratio $M = 0.5$, for example, all rays emitted in the angular interval up to $\theta = 5^\circ$ will pass through a circle demagnified by a factor of $M' = 0.75$ relative to the emitting fiber core diameter $D = 0.4$ mm; i.e., the rays will pass through a circular spot of diameter 0.3 mm. This can be seen from the curve labeled $\theta = 5^\circ$ in Figure 25. Note that the curve labeled $\theta = 5^\circ$, for all rays in the interval 0° to 5° , has a minimum demagnification of 0.725 relative to the fiber core diameter, at the "object-image" ratio $(b+R)/(a+R) = 0.41$, corresponding to a distance $b = 0.82$ mm. The condition for total internal reflection is satisfied for the data of Figure 25.

If only ray emission angles in the interval $0^\circ \leq \theta \leq 3^\circ$ are considered, then it is possible to achieve a demagnification of $M' = 0.44$ relative to the fiber core diameter, for a distance ratio $M = (b+R)/(a+R) = 0.265$, at distance $b = 0.6$ mm beyond the exit region of the half-sphere. This can be seen from the curve labeled $\theta = 3^\circ$ in Figure 25.

Even though the numerical aperture of the fiber used for DOI is 0.22 and corresponds to $\theta = 12.7^\circ$, the typical injection schemes used result in incident angles on the input fiber face in the range $0^\circ \leq \theta \leq 2.9^\circ$. Therefore, the angular limits on θ for the calculations represented in Figure 25 are practical. For $\theta = 3^\circ$ the demagnification factor of 0.44 would give a fluence higher than that in the core by the factor $(1/0.44)^2 = 5.16$. This would give a considerable margin for offsetting Fresnel losses from reflection, for example, in an uncoated system. The fluence enhancement would be 4.36, considering Fresnel losses for a half-sphere with $n_1 = 1.83$.

Similar demagnification results are given in Figure 26 for a half-sphere of the same size but with $n_1 = 1.45$ (fused silica). For rays emitted up to $\theta = 3^\circ$, the demagnification is 0.71 for $(b+R)/(a+R) = 0.37$. The condition for total internal reflection is not satisfied at $\theta = -2^\circ$ for $h \leq 0.01$ mm, nor at $\theta = -3^\circ$ for $h < 0.08$ mm.

Figure 25. Demagnification Factor for Spot Size in Plane at Distance b for Half-Sphere Arrangement in Figure 16, Versus Ratio of Image to Object Distance, M , From Simple Geometric Optics. (The calculations are for lens material LaSF9 with $n_1 = 1.83$ and $R = 1.5$ mm. All curves are for the full radial range $h \leq 0.2$ mm on a 0.4-mm diameter emitting fiber. Each curve corresponds to the angular interval from $\theta = 0^\circ$ up to the value indicated. Each curve shows a maximum demagnification at its minimum.)

Figure 26. Demagnification Factor for Spot Size in Plane at Distance b for Half-Sphere Arrangement in Figure 16, Versus Simple Geometric Optics Image/Object Distance Factor, M , and Corresponding Distance b . (Calculations are for fused silica lens material with $n_1 = 1.45$ and for full range in radial distance $h \leq 0.2$ mm on a 0.4-mm diameter emitting fiber. The lens radius is $R = 1.5$ mm. Each curve corresponds to the angular interval on θ from 0° to the value indicated. The minimum of each curve corresponds to the maximum de-magnification factor possible for the indicated interval on θ .)

Accomplishments

One of the benefits of using fiber optics for the transmission of light energy is that the fiber can be routed in nearly limitless geometric paths. Limitations do exist in routing a fiber through a very small radius bend, however. In the case of DOI (direct optical initiation), a fiber of diameter 400 μm is used which is limited to a long-term minimum bend radius of approximately 75 mm. Bends of smaller radius either result in premature breakage or excessive loss at the core/cladding interface. In some applications, such as DOI, it is necessary to turn the fiber beam through 90° within a small region in space. Two designs were investigated. In one of the designs, a small sphere lens is used to focus the diverging exit fiber beam through a small right-angle prism to a region just beyond the exit face of the prism. In the other design, a single element in the form of a half-sphere lens accomplishes both the converging effect on the exit beam and the 90° turn through total internal reflection at the half-sphere diametrical face set at 45° to the exit beam axis. Special ferrule sleeves were designed to position both optical devices on the ends of standard SMA 906 optical connectors. Prototype units were fabricated that accomplished a 90° turn of the exit fiber beam within a radius of approximately 1.5 mm, which is only 2 percent of the minimum bend radius of the fiber.

Intensity measurements in the transmitted beams were made by moving a small-diameter fiber through the center of the beam. An analysis was made to determine the maximum sensor fiber diameter relative to the $1/e^2$ diameter of an assumed Gaussian beam profile for which the measured distribution would be within a desired percentage of the actual Gaussian profile.

The paths of rays from the emitting fiber face were traced through both designs of the right-angle devices. Conditions were determined for which the 90°-turned beam passed through a plane in space with the same or greater fluence as that at the emitting fiber face.

Future Work

More devices of both types for turning an exit fiber beam through 90° will be designed in accordance with the results of the ray tracing analyses. Laser-induced damage testing at the DOI laser wavelength of 1.064 μm will be done to determine thresholds for laser damage of the devices.

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Appendix

Equations 13 through 19 of the text can be derived with the aid of Figure A-1 which is essentially Figure 15 of the text with designated angles and distances.

Let an (x, y) coordinate system be positioned with origin at the center of the emitting fiber with the x -axis along the emitting fiber axis, passing through the center of the sphere lens of radius R . The equation of the path representing a ray emitted at angle θ at radial distance h from the fiber center is

$$y = x \tan \theta + h. \quad (\text{A-1})$$

The equation of the circle representing the lens cross section relative to the (x, y) system is

$$[x - (a + R)]^2 + y^2 = R^2. \quad (\text{A-2})$$

When y is eliminated between A-1 and A-2, the x_1 coordinate of the point of intersection of the ray with the lens is the smallest root of the quadratic

$$A_1 x_1^2 + B_1 x_1 + C_1 = 0 \quad (\text{A-3})$$

where

$$\begin{cases} A_1 = 1 + \tan^2 \theta \\ B_1 = 2[h \tan \theta - a - R] \\ C_1 = (a + R)^2 + h^2 - R^2. \end{cases}$$

The corresponding y coordinate of the point of intersection is obtained from Equation A-1

$$y_1 = x_1 \tan \theta + h, \quad (\text{A-4})$$

and hence the angle ω_1 , in Figure A-1 is

$$\omega_1 = \arcsin \left(\frac{y_1}{R} \right). \quad (\text{A-5})$$

The angle of incidence of the ray at the lens surface is

$$i = \theta + \omega_1 \quad (\text{A-6})$$

Figure A-1. Sphere Lens/Prism Geometry of Figure 15 of Text (with angle and distance designations added for derivation of Equations 13 through 19 of text)

and the angle of refraction as the ray enters the lens at the point (x_1, y_1) is found from Snell's law to be

$$\gamma = \arcsin\left(\frac{\sin i}{n_1}\right), \quad (\text{A-7})$$

where n_1 is the refractive index of the lens medium and it is assumed the lens is surrounded by air of unity refractive index.

By symmetry, the angle of incidence of the ray within the lens as it exits at the point (x_2, y_2) is equal to the angle of refraction γ in equation A-7, as can be seen from Figure A-1. From the triangle defined by the lens center and (x_1, y_1) and (x_2, y_2) , the angle ω_2 is given by

$$\begin{aligned} \omega_2 &= \pi - [\omega_1 + \pi - 2\gamma] \\ &= 2\gamma - \omega_1. \end{aligned} \quad (\text{A-8})$$

Therefore, the coordinates of the point (x_2, y_2) , are

$$\left. \begin{aligned} y_2 &= R \sin \omega_2 \\ x_2 &= a + R + R \cos \omega_2 \end{aligned} \right\} \quad (\text{A-9})$$

Again, by symmetry in Figure A-1, the angle of refraction as the ray exits the lens at (x_2, y_2) , is the same as the angle of incidence i as the ray enters at (x_1, y_1) . Thus, the equation representing the ray path as it exits the lens is

$$\begin{aligned} \frac{y - y_2}{x - x_2} &= \tan(\omega_2 - i), \\ \text{or} \quad y &= y_2 + (x - x_2) \tan(\omega_2 - i). \end{aligned} \quad (\text{A-10})$$

The height y_3 at which the ray is incident on the prism face is obtained from equation A-10.

$$\left. \begin{aligned} y_3 &= y_2 + (x_3 - x_2) \tan(\omega_2 - i) \\ \text{where} \quad x_3 &= a + 2R + b. \end{aligned} \right\} \quad (\text{A-11})$$

The angle of incidence at the prism face is

$$i_3 = \omega_2 - i \quad (\text{A-12})$$

and so the angle of refraction as the ray enters the prism of refractive index n_2 is obtained from Snell's law to be

$$\gamma_3 = \arcsin\left(\frac{\sin i_3}{n_2}\right). \quad (\text{A-13})$$

The equation of the line representing the diagonal face of the prism relative to the (x, y) coordinate system is

$$y = \frac{L}{2} + x_3 - x. \quad (\text{A-14})$$

The equation of the path of the ray as it enters the prism at point (x_3, y_3) is

$$y = (x - x_3)\tan\gamma_3 + y_3. \quad (\text{A-15})$$

The point (x_4, y_4) at which the ray arrives at the diagonal face can be found from equations A-14 and A-15. First, eliminating y gives

$$x_4 = \frac{\frac{L}{2} + x_3 - y_3 + x_3 \tan\gamma_3}{1 + \tan\gamma_3}, \quad (\text{A-16})$$

and then

$$y_4 = \frac{L}{2} + x_3 - x_4. \quad (\text{A-17})$$

The angle of incidence/reflection, i_4 , at the diagonal face is

$$i_4 = \frac{\pi}{4} - \gamma_3, \quad (\text{A-18})$$

which applies whether the angle γ_3 is positive or negative. It is assumed that the prism is surrounded by air, and it follows from Snell's law that total internal reflection will occur within the prism at the diagonal face provided

$$i_4 > \arcsin\left(\frac{1}{n_2}\right). \quad (\text{A-19})$$

If $i_4 < \arcsin(1/n_2)$, then the ray will pass through the diagonal face.

Tracing the path of the ray after internal reflection at the diagonal face can be accomplished using an (x', y') coordinate system with origin at point $(x_3, L/2)$ in the (x, y) system, but with coordinates x' and y' perpendicular, respectively, to x and y . Therefore, the equation of the path in the (x', y') system, after reflection from the diagonal face at (x_4, y_4) is given by

$$\frac{y' - [x_4 - (a + 2R + b)]}{x' - \left(\frac{L}{2} - y_4\right)} = \tan\left(i_4 - \frac{\pi}{4}\right). \quad (\text{A-20})$$

The y'_5 coordinate at the point of intersection of the ray with the exit prism face at $x' = L$ is obtained from Equation A-20.

$$y'_5 = x_4 - x_3 + \left(\frac{L}{2} + y_4\right) \tan\left(i_4 - \frac{\pi}{4}\right). \quad (\text{A-21})$$

From Snell's law the angle of refraction as the ray leaves the prism at (L, y'_5) is

$$\gamma_5 = \arcsin\left[n_2 \sin\left(i_4 - \frac{\pi}{4}\right)\right]. \quad (\text{A-22})$$

The equation of the path of the ray as it exits the prism is therefore

$$\frac{y' - y'_5}{x' - L} = \tan \gamma_5 \quad (\text{A-23})$$

and hence the coordinate y'_6 in the plane at distance d beyond the prism face is

$$y'_6 = y'_5 + d \tan \gamma_5. \quad (\text{A-24})$$

The distance of the ray, in the plane at d , from the axis perpendicular to the center of the exit prism face is

$$y' = y'_6 - \frac{L}{2}. \quad (\text{A-25})$$

Equations 13 and 14 of the text can be obtained by beginning with Equation A-25 and then using Equation A-24 to eliminate y'_6 , Equation A-21 to eliminate y'_5 , Equations A-16, A-17 to eliminate x_4, y_4 , Equation A-11 to eliminate x_3, y_3 , and Equation A-9 to eliminate x_2, y_2 . In the course of these eliminations, Equations A-6, A-12, A-13, and A-18 are also combined with Equation A-22 to give the result $\gamma_5 = 2(\gamma - \omega_1) - \theta$ which is defined as the angle u .

If h is replaced by $-h$ and the angle θ is replaced by $-\theta$, then the transformations in the various distances and angles that occur as a result can be obtained from equations A-4 through A-22, and the results are tabulated in Table A-1.

Table A-1. Effect of Replacing h With $-h$ and θ With $-\theta$

$y_1 \rightarrow -y_1$	x_1 unchanged
$\omega_1 \rightarrow -\omega_1$	x_2 unchanged
$i \rightarrow -i$	x_3 unchanged
$\gamma \rightarrow -\gamma$	
$\omega_2 \rightarrow -\omega_2$	
$y_2 \rightarrow -y_2$	
$y_3 \rightarrow -y_3$	
$i_3 \rightarrow -i_3$	
$\gamma_5 \rightarrow -\gamma_5$	
$\gamma_3 \rightarrow -\gamma_3$	

When the transformations given in the table are combined with Equation A-25 and all the related expressions for distances and angles, it is found that

$$y'(-h, -\theta) = -y'(h, \theta), \quad (\text{A-26})$$

which is the first expression in Equation 19 of the text. The second expression in Equation 19 can be obtained by noting that x_1 is always positive and then substituting the appropriate combinations of positive and negative values of h and θ in Equation 14 and then determining the effect of the sign changes on y' in Equation 13.