Technical Memorandum 100

Fiber Optics: Theory and Applications

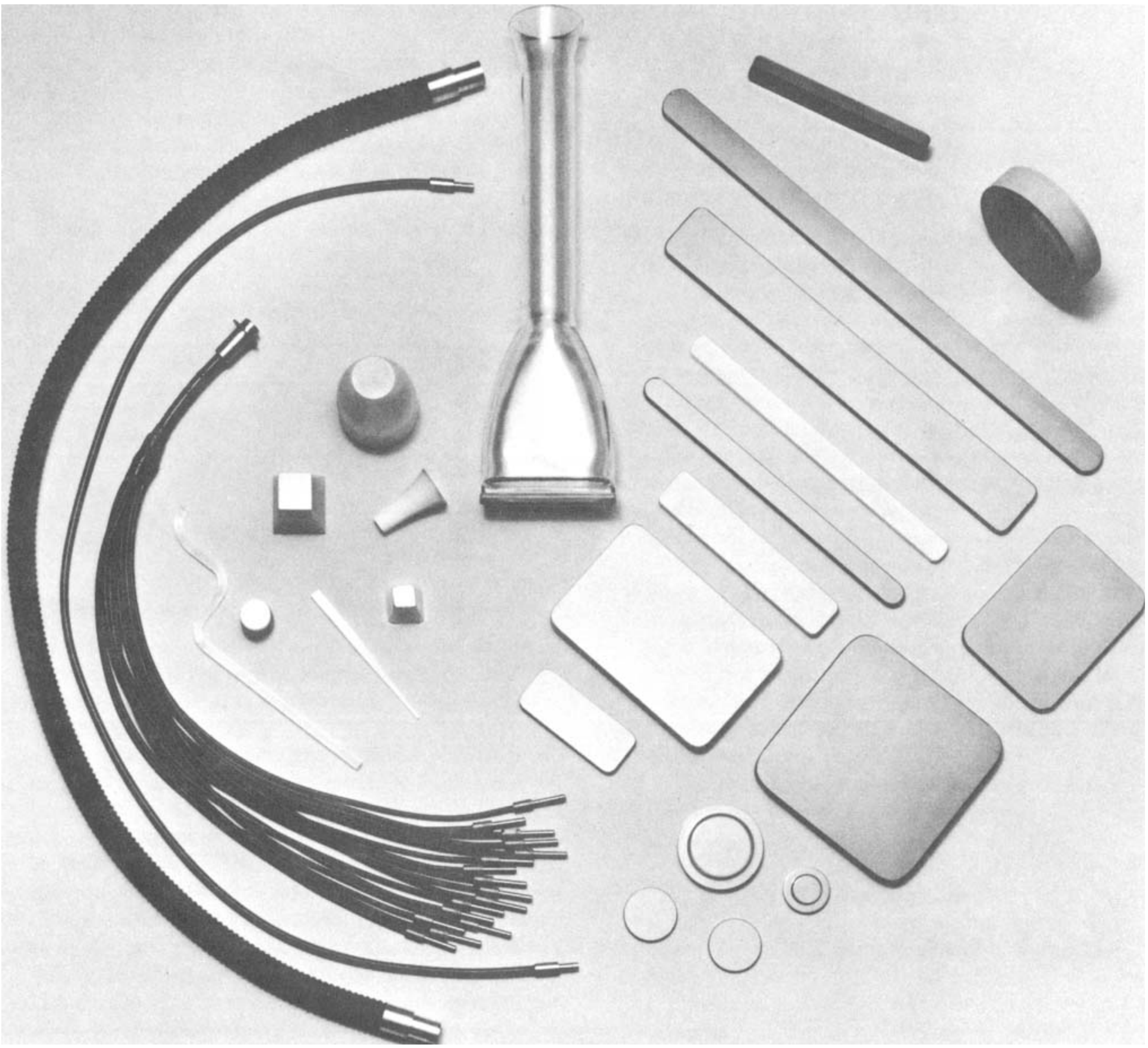

TABLE OF CONTENTS

Fiber Optics Fundamentals

The science of fiber optics deals with the transmission or guidance of light (rays or waveguide modes in the optical region of the spectrum) along transparent fibers of glass, plastic, or a similar medium. The phenomenon responsible for the fiber or light-pipe performance is the law of total internal reflection.

Total Internal Reflection

A ray of light, incident upon the *interface* between two transparent optical materials having different indices of refraction, will be totally internally reflected (rather than refracted) if

(1) the ray is incident upon the interface from the direction of the more dense material and
(2) the angle made by the ray with the normal to the interface is greater than some critical angle, the latter being dependent only on the indices of refraction of the media (see Figure 1).

Rays may be classified as meridional and skew. Meridional rays are those that pass through the axis of a fiber while being internally reflected. Skew rays are those that never intersect the fiber axis although their behavior patterns resemble those of meridional rays in all other respects. For convenience, this discussion will deal only with the geometric optics of meridional ray tracing.

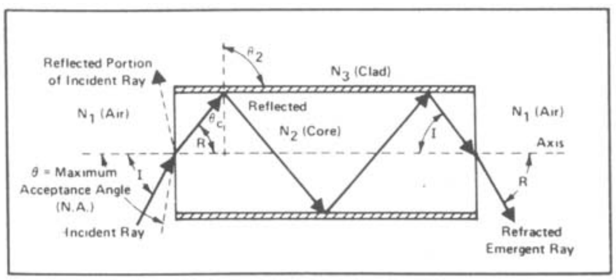

Figure* 1 *Refraction, Reflection, and Numerical Aperture

An off-axis ray of light traversing a fiber 50 microns in diameter may be reflected 3000 times per foot of fiber length. This number increases in direct proportion to diameter decrease.

Total internal reflection between two transparent optical media results in a loss of less than 0.001 percent per reflection; thus a *useful* quantity of illumination can be transported. This spectral reflectance differs significantly from that of aluminum (shown graphically in Figure 2). An aluminum mirror cladding on a glass fiber core would sustain a loss of approximately 10 percent per reflection, a level that could not be tolerated in practical fiber optics.

As indicated in Figure 1, the angle of reflection is equal to the angle of incidence. (By definition, the angle is that measured between the ray and the normal to the interface at the point of reflection.)

Light is transmitted down the length of a fiber at a constant angle with the fiber axis. Scattering from the

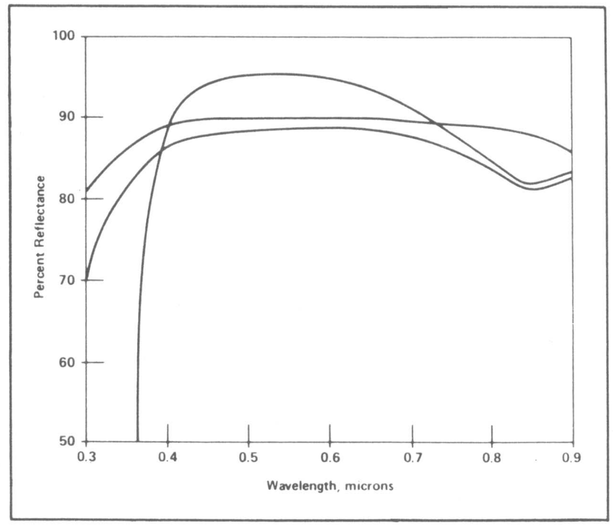

Figure 2 Aluminum Mirror Reflectance

true geometric path can occur, however, as a result of

(1) imperfections in the bulk of the fiber;
(2) irregularities in the core/clad interface of the fiber; and
(3) surface scattering upon entry.

In the first two instances, light will be scattered in proportion to fiber length, depending upon the angle of incidence. To be functional, therefore, long fibers must have an optical quality superior to that of short fibers. Surface scattering occurs readily if optical polishing has not produced a surface that is perpendicular to the axis of the fiber; pits, scratches, and scuffs diffuse light very rapidly.

The speed of light in matter is less than the speed of light in air, and the change in velocity that occurs when light passes from one medium to another results in refraction. It should be noted that a portion of the light incident on a boundary surface is not transmitted but is instead reflected back into the air. That portion that *is* transmitted is *totally reflected* from the sides, assuming that the angle is less than the critical angle (see Figure 1).

The relationship between the angle of incidence I and the angle of refraction R is expressed by Snell's law as

$$N_1 \sin I = N_2 \sin R$$

where N_1 is the index of refraction of air and N_2 the index of refraction of the core. Since $N_1 = 1$ for all practical purposes, the refractive index of the core becomes

$$N_2 = \sin I / \sin R$$

Numerical Aperture

Numerical aperture (abbreviated N.A. in this paper) is a basic descriptive characteristic of specific fibers. It can be thought of as representing the size or "degree of openness" of the input acceptance cone (Figure 3). Mathematically, numerical aperture is defined as the

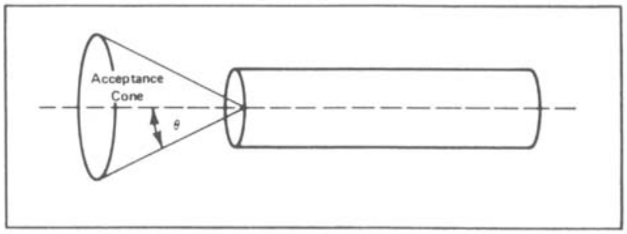

Figure 3 Numerical Aperture

sine of the half-angle of the acceptance cone (sin θ*).*

The light-gathering power or flux-carrying capacity of a fiber is numerically equal to the square of the numerical aperture, which is the ratio between the area of a unit sphere within the acceptance cone* and the area of a hemisphere (2π solid angle). A fiber with a numerical aperture of 0.66 has 43 percent as much flux-carrying capacity as a fiber with a numerical aperture of l.0; i.e., $(0.66)^2/(1.0)^2 = 0.43$.

Snell's law can be used to calculate the maximum angle within which light will be accepted into and conducted through a fiber (see Figure 1):

$$N_1 \sin \theta_{max}(N^2{}_2 - N^2{}_3)^{1/2}$$

In this equation, sin θ max is the numerical aperture, N_1 the refractive index of air (1.00), N_2 the refractive index of the core, and N_3 the refractive index of the clad. As light emerges from the more dense medium (glass) into a less dense medium such as air, it is again refracted. The angle of refraction is greater than the angle of incidence *(R > I)* at emergence only; and because *R* is by necessity 90 degrees, there must be a limiting value of *I* beyond which no incident ray would be refracted and emerge into the air. This becomes the critical angle, and rays that strike at a greater angle are totally reflected.

It should be noted that this formula for the calculation of numerical aperture does not take into account striae, surface irregularities, and diffraction, all of which tend to decollimate the beam bundle.

Source Distributions

A lambertian source plane is one that looks equally bright from all directions. It emits a flux proportional to the cosine of the angle from the normal. Matte white paper and phosphors are approximate examples of such source planes, and the light diffused by opal glass is a close approximation for most measurements.

In the lambertian case, the flux contained out to an angle θ is proportional to $\sin^2 \theta$.

Input-Output Phenomena

If a ray is incident at angle θ*,* it will ideally emerge from a fiber at angle θ. In practice, however, the azimuthal angle on emergence varies so rapidly with θ*,* the length and diameter of the fiber, etc. that the emerging ray spreads to fill an annulus of a cone twice

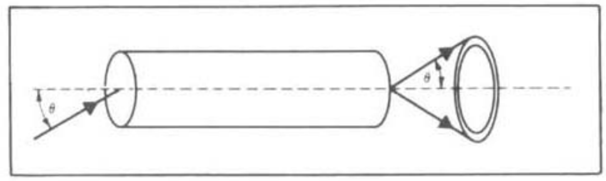

Figure 4 Fiber Light Transmission

angle θ*,* as shown in Figure 4.

In a two-lens system, where the output light is fed from a fiber annulus back into a second lens (Figure *5),* the light will be distributed over a 360-degree angle and only a small fraction of it will strike the second lens. This effect is important in fiber-optic system design: in

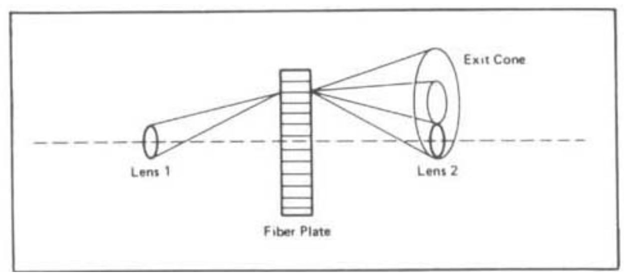

Figure 5 Projection System Transmission

general, fiber optics should be utilized as image or light *transporters* rather than as focusing components.

The exit end of a fiber will act as a prism if it is not cut perpendicular to the fiber axis. A bias cut will tip the exit cone as shown in Figure 6. Thus

$$\beta = \sin^{-1} [(N_2/N_1)\sin \alpha] - \alpha$$

$$\cong[(N2 /N_1) - 1]\ a \text{ (for small angles)}$$

where β is the axis of the deflected ray and α is the cut angle to the normal of the fiber.

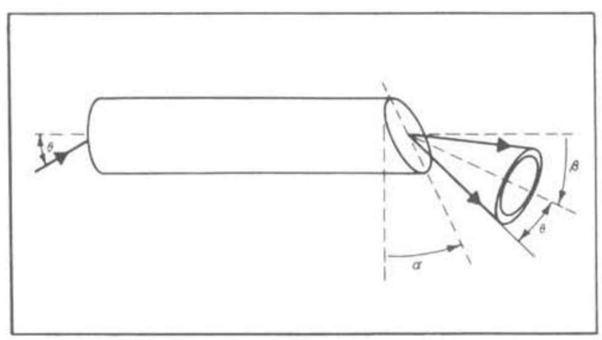

Figure 6 Biased End Cut

The preservation of angle θ on exit is only an approximation. Diffraction at the ends, bending, striae, and surface roughness will cause decollimation or opening of the annulus. The striae and roughness

* Acceptance cone angles are expressed in solid angles.

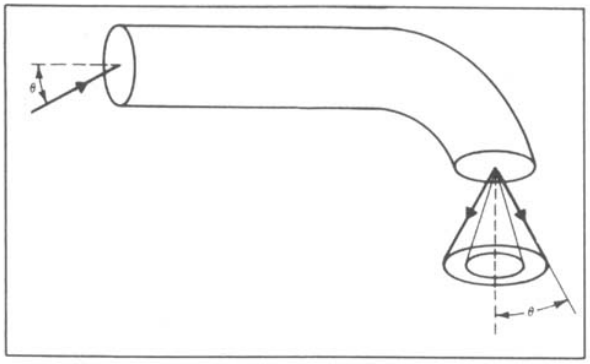

Figure 7 Bent-Fiber Transmission

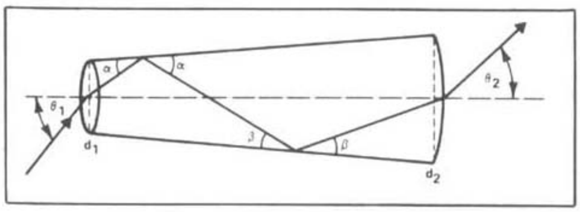

Figure 8 Tapered-Fiber Transmission

cause progressive decollimation; diffraction and bending may be regarded as terminal factors (see Figure 7). The effect is most apparent in systems in which collimated transmission is emphasized.

Tapered fibers are governed by one important law,

$$d_1 \sin \theta_1 = d_2 \sin \theta_2$$

where diameters and angles are as shown in Figure 8. The angle of reflection of a light ray is equal to the angle of incidence; therefore, light entering the small end of a fiber becomes more collimated as the diameter increases because the reflecting surface is not parallel to the fiber axis. Collimated light entering tapered fibers at the large end, on the other hand, becomes decollimated, and if the angle of incidence exceeds the acceptance angle, it will pass through the side of the fiber. The error perhaps most frequently made by the novice is to attempt to condense an area of light that is lambertian. As illustrated in Figure 9, this merely "throws" light out the sides. If the in coming light is in a small angle, the outgoing flux per

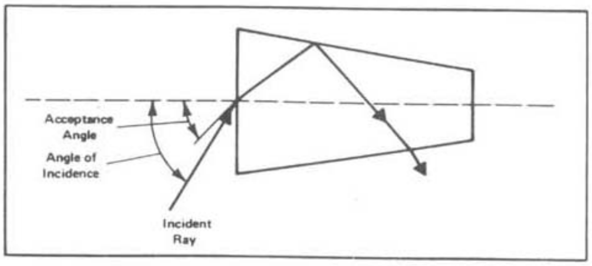

Figure 9 Large-End-to-Small-End Transmission

unit area can be increased.

When working with a system of the "Mae West" variety (see Figure 10), it is important to remember that the smallest diameter determines the acceptance angle of the system. This is in conformity with the law previously

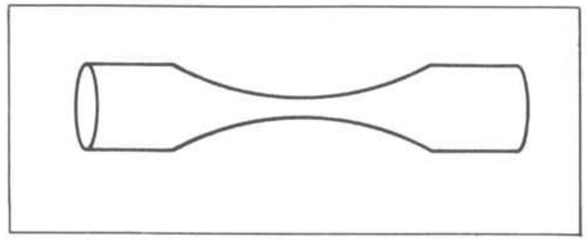

Figure 10 Mae West System

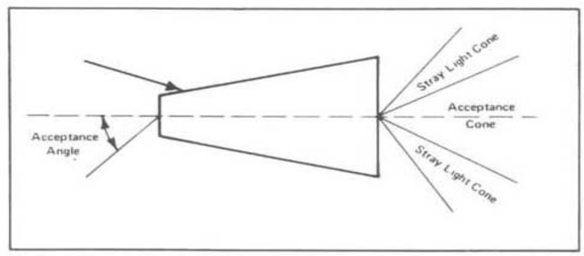

Figure 11 Effect of Light Entering through Side

cited which governs tapered fibers.

Light entering the side of a fiber can be trapped if the angle of incidence is greater than the critical angle. The stray-light cone thus produced forms the basis for one type of injection lighting (see Figure 11). Loss of contrast, however, renders the technique of little general use.

Depth of Focus

Depth of focus for a fiber system as for a lens system depends on the f/number or numerical aperture (see Figure 1 2). It is calculated from the formula

$$d'/2\Delta = \tan\theta$$

$$\cong \sin\theta \text{ (for small angles)}$$

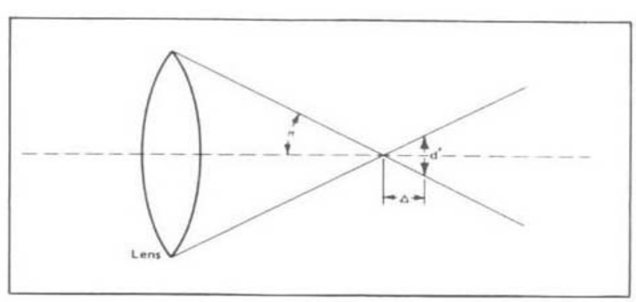

Figure 12 Depth of Focus

where *d'* is the desired resolution diameter and Δ the depth of focus. Thus, a fiber having a numerical aperture of 0.66 would require a depth of focus of approximately 0.00 1 inch to resolve a spot 0.002 inch in diameter. (If N.A. = sin θ = 0.66, θ = 41.5°; tan 41.5° = 0.88; 0.88 = 0.002/2Δ; = 0.0011.)

Image Formation

Fiber optics can never "form" an image or transport an "unformed" image. The end surfaces of fiber optics should in all cases be image surfaces. The ability of a *lens* to form an image depends on making a phase transformation on a wave front. Although fibers carry phase information, each fiber acts as a diffraction grating because of the multiplicity of wave-guide modes (and hence, propagation constant). Moreover, minute diameter variations from fiber to fiber produce enormous phase changes.

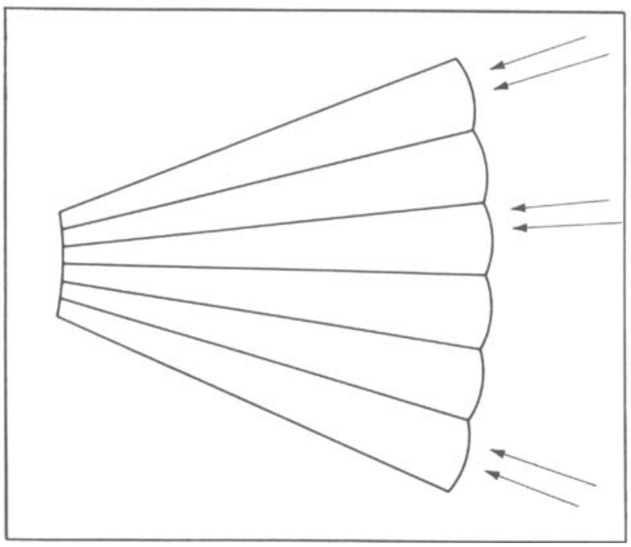

Figure 13 Eye of a House Fly

An exception to these general rules is seen in the house fly. Its eye is an array of tapered fibers, each forming a narrow acceptance angle and each looking in a different direction (see Figure 13).

Fiber Arrays and Cladding

The discussion to this point has dealt primarily with single fibers. When unclad fibers are bunched together in an orderly array, light will pass from one to the other because evanescent waves that exist close to a fiber surface can be trapped by an adjacent fiber. For this and other reasons, optical fibers are made with a low-index-of-refraction cladding of sufficient thickness to insulate the light-conducting channel from the outside world. This cladding is most frequently glass, and in fused arrays it bonds the fibers to form a solid material.

In optical mosaics, which are fused assemblies, a second cladding of opaque material is commonly applied around each fiber to absorb light outside the acceptance angle. Such a mosaic is said to have extra mural absorption (E.M.A.). Figure 14 illustrates how a phosphor emits light in all directions. Light inside the acceptance angle will form an image; light outside will be scattered. The phosphor also emits light that enters the cladding portion of the fiber. This light is conducted through the optical mosaic as part of the background light rather than as image light. The scattered light will not be observed by the eye viewing within the acceptance angle. It will, however, degrade contrast in direct film printing.

Resolution

The resolving power of a fiber-optic device in motion is well defined. It is that of a flying spot scanner of spot size equal to the fiber core size. As a rule, 0.8 photographic line pairs per fiber diameter can be resolved if there is a high-contrast target. The resolution of a static fiber-optic device is less well defined. Only about 0.5 photographic line pairs per fiber diameter can be resolved, and picture quality is poor. It is wise, therefore, to be conservative in estimating resolving power.

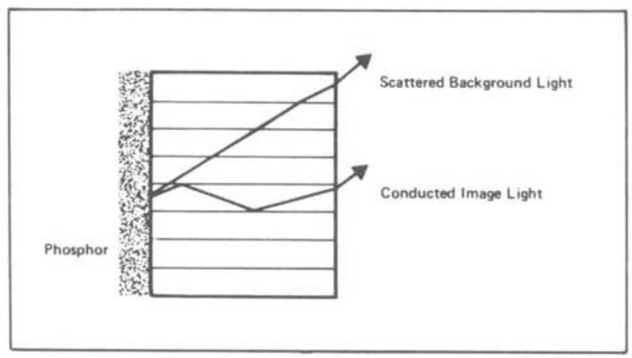

Figure 14 Lambertian Transmission in an Optical Mosaic

In terms of information theory, static resolving power for line pairs is actually higher than dynamic resolving power. Nevertheless, in terms of quick recognition, it is empirically as stated. The apparent resolving power of static systems for random small figures (to be differentiated from large figures with long edges) is approximately half as good as that of dynamic systems in shape recognition but two-thirds as good in counting the number of figures. Typical static system resolution is plotted for various core sizes in Figure 1 5.

For best visual results, one should present a static mosaic to the eye with just enough magnification to resolve the fiber structure. More magnification causes the fiber structure to become distracting and hampers the recognition process.

The resolving power of a system made up of more than a single optical mosaic may be represented as follows,

$1/r^2_{system} = 1/r^2_1 + 1/r^2_2 + 1/r^2_3 + \ldots$ where r_1, r_2, r_3, etc. are the individual resolving powers of the system elements in line pairs per millimeter. Moreover,

$$r_1 = 1/2d_1$$

where d_1 is the fiber diameter in millimeters. Actually, a static system of four cascaded 10-micron mosaics gives better picture appearance than a single 20-micron mosaic.

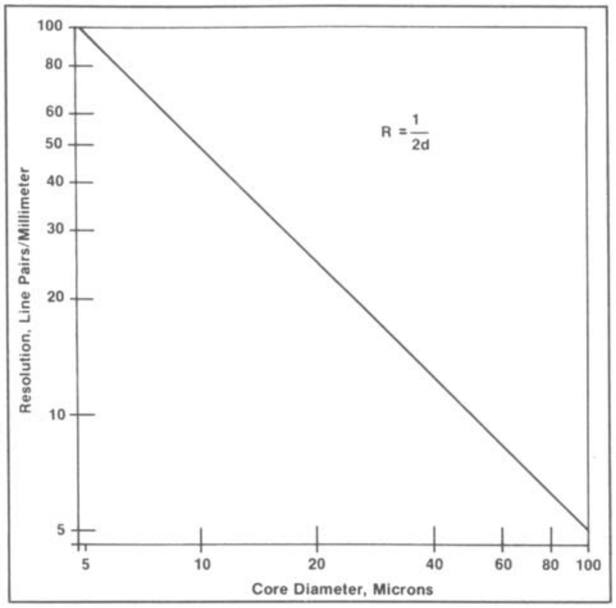

Figure 15 Fiber Optic Resolution

Fiber Optics Configurations

Fiber optics are used in a variety of configurations. The descriptions that follow reflect only the current state of the art and are oriented primarily toward glass fibers. Pertinent differences between glass and plastic media will be dealt with in the subsequent discussion on applications.

FIBER OPTIC NON-IMAGING CONFIGURATIONS

Single Fibers

Single fibers, the simplest form of fiber optics, can be used to conduct light and images to and from small regions. Low order waveguides can be made from fibers having very small diameters. Active fibers made from suitable core materials can be made to show laser action and amplify spontaneous or injected light. Low loss fibers can be used to distances of a few hundred meters between repeaters. Complex single fibers may be made for special purposes with more than one cladding just as individual fibers may be made with more than one core.

Single fibers are readily available in diameters from about 0.020 to 2.0 millimeters, but smaller or larger structures may be made for special applications. Individual fibers tend to become difficult to handle in sizes less than about 0.05 millimeters in diameter, but they may be fabricated for waveguide applications with cores as small as the wavelength of light and relatively thick cladding to facilitate handling.

Glass combinations can readily provide multimode fibers having good mechanical properties, and having numerical apertures of 1.0 or greater, although air clad fibers can be made having numerical apertures up to 1.4. Air-clad fibers generally require individual plastic sheaths and are less desirable than glass clad glass fibers. Most commercial glass fibers have a numerical aperture of approximately 0.4-1.1, a loss of 1-2 decibels per meter, and useful spectral transmission from about 0.4 microns to 2.2 microns, and exhibit mechanical strengths in excess of 20,000 psi. Special intermediate loss glass fibers having numerical aperture of approximately 0.55, and loss of 0.3 to 0.5 decibels per meter and good mechanical properties are readily available for optical communications applications in lengths up to several thousand meters.

Special ultraviolet transmitting glasses may be used to provide transmission as low as 350 nanometers, and arsenic trisulfide or silver chloride fibers permit infrared operation to 6-8 microns. Air-clad silica fibers with protective tubing spaced from the core fiber are available for limited applications.

Maximum operating temperatures on glass fibers may be typically between 300 °C and 400 °C, although intermittent exposure to temperatures over 600 °C are possible if the fibers are suitably mounted. Silica fibers can be operated at much higher temperatures. Special fibers of glass or silica can be made more resistant to neutrons, x-ray, gamma, or ionized particle radiation than commonly used glasses.

Light Guides

Light conduit is made up of fibers randomly collected or bunched in a group and is governed by the same principles as single fibers. Typical bundles are 1/32 to 1/4 inch in diameter.

The safe bending radius of a light conduit is determined by such factors as bundle size, fiber size, and nature of sheathing. These factors vary with application requirements and must be considered in design. If fiber diameters are 0.0025 inch or less, the bending radius is usually limited by the bending radius of the sheathing.

Because light or image transport is the main function of fiber optics, transmission capabilities and characteristics of fibers must be carefully controlled. Transmission depends primarily on input and output surface reflection losses, packing fraction, core/clad interface scattering, and bulk absorption. It depends secondarily on fiber size, homogeneity of core glass, and defects in core and cladding. The primary factors are design considerations; the secondary factors are manufacturing considerations.

Reflection losses vary with the optical density of the core glass. As shown in Figure 16, the high-refractive-index glass used for fibers of large numerical aperture has a relatively high percent reflectance.

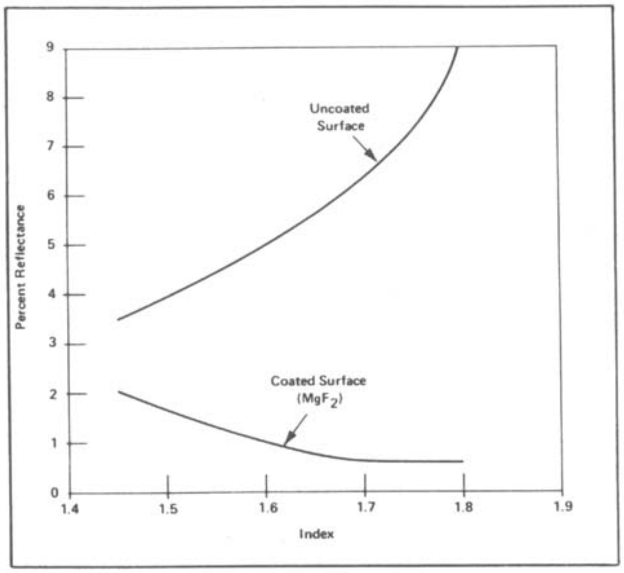

Figure 16 Reflection Loss Variation with Index of Refraction

Because each individual light conduit application involves a glass bundle with a specific packing fraction, refractive index, and length, transmission losses can be determined and the output to be expected from a known input can be calculated. Take, for example, a 50-micron element format with a core glass having a refractive index of 1.625. If the input illumination inside the acceptance cone is 100% and the packing fraction is 85%, transmission after packing-fraction loss is 100 x 0.85 or 85%. The reflection loss for each surface (entrance and exit), calculated from the expression $[(N_2-N_1)/(N_2+N1)]^2$ where N_1 is the refractive index of air (1.0) and N_2 the refractive index of the core glass, is 5.7%; thus transmission at each surface is 94.3%. Net transmission after input reflection is therefore 0.85 x 0.943 or 80.2%. Bulk absorption and interface scattering are responsible for a further loss of 6.0% per foot of bundle length or 53.9% (over a length of 10 feet. Net transmission after 10 feet is therefore 0.802 x 0.539 or 43.2%. Exit surface transmission is, as previously calculated, 94.3%, leaving a final net transmission of 0.432 x 0.943 or 40.7%. In other words, a 10-foot fiber-optic bundle of the type described above will transmit only 40% of the light striking the input surface.

Flexible fiber bundles are used for data processing, scanning, counting, and sizing. They also have special utility in situations where "cold" light is required, as in operating rooms and explosive atmospheres.

Plastic versus Glass Fibers

Although plastic fibers do not have the dimensional stability and environmental durability of glass, they are acceptable for certain applications. Those currently available, most commonly methyl meth-acrylate, exhibit an acceptance angle of only about 35 degrees (cone half-angle), which imposes a limitation on their applicability. Their operating temperature range, -40 to 180° F, imposes a further limitation. Thus, plastic fiber optics can never be used in electron tube structures, which must be processed at elevated temperatures; relatively low environmental temperatures, on the other hand, cause plastic fibers to shrink. Glass fibers possess slightly better transmission characteristics in the ultraviolet region of the spectrum and much better characteristics in the near-infrared over a numerical aperture range of 0.2 to 1 .0. Plastic fibers are less affected by nuclear radiation over extended periods of time.

The chief advantages of plastic are its flexibility and ease of end finish. Plastic fiber ends can be cut with a razor blade. Glass must be polished to be effective; it accepts a better polish than plastic and shows little or no deterioration with time or wear. The use of glass is indicated for most high-reliability applications.

FIBER IMAGING CONFIGURATIONS

Flexible Imagescopes

The imagescope is an image transfer device capable of monitoring remote events and/or inspecting otherwise inaccessible or hazardous areas. The flexible scopes are fabricated from thousands of 0.002-inch flexible multifibers (basic elements 10 microns or less in diameter), aligned to permit end-to-end transmission of a high-resolution image.

Attainable resolution and transmission are those predicted by theory for the fiber size in question. Typical resolution is 50 line pairs per millimeter. Stainless steel hardware is normally used to prevent dust or liquid from reaching the fibers. Lengths fabricated to date range from 2 to 1 5 feet.

Most imagescopes are designed and produced to meet the specific needs of the user.

Image Combiners/Image Duplicators

Another application of rigid fiber optic structures is the *Image Combiner/Image Duplicator.* In the combiner mode it permits the precise superposition of two images focused at the dual aperture end to be displayed on the single aperture end. This combining operation, by way of line-by-line interlacing, provides a means of overlaying passive information (maps, grids, reticles, etc.) or generated information (such as from a cathode ray tube) with actual real time information.

Since the device also functions in the reciprocal mode, an image focused on the single aperture end is duplicated in each window of the dual aperture end. This image duplication is achieved by dissecting the

input image point-by-point and then dividing it into two images on a line-by-line basis. The symmetric unit shown in Figure 17 will give two output images, each one having one-half the brightness and resolution of the original image.

These devices should be particularly useful in parallel optical image processing, but also have applications in many other optical systems.

These units are solid, single piece structures and are small, light weight, rugged, and free from the normal vibration and alignment problems of functionally similar

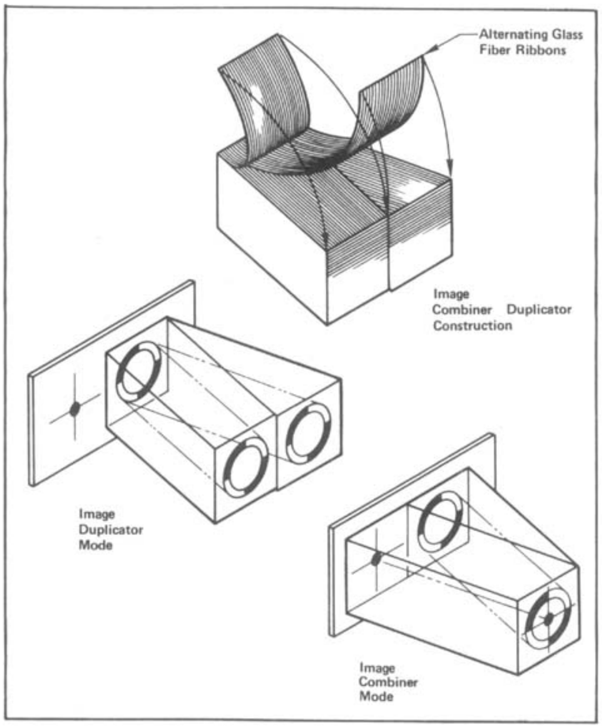

Figure 17 Image Combiners/Image Duplicators

conventional optical systems.

FUSED IMAGING CONFIGURATIONS

Optical mosaics are fused blocks of aligned fibers. They may be thick or thin, large or small, tapered, distorted, or bent. The calculation of transmission through an optical mosaic must take into account the following factors:

(1) As in the case of light conduit, reflection off both entrance and exit surfaces is expressed by the Fresnel equation. For normal incidence, this energy reflection has a value equal to $[(N^2 - N_1)/(N_2 + N_1)]^2$, where N_1 is the refractive index of air and N_2 the refractive index of the core glass. Figure 16 illustrates how glasses with varying indices of refraction differ in reflectance.

(2) The area occupied by the cladding is wasted and varies from 8 to 30 percent (see Figure 18). The cladding thickness required to prevent cross talk* depends upon fiber thickness, wavelength, indices of refraction, and angle of. incidence. The resonance theory of cross talk is beyond the scope of this discussion, but one negative

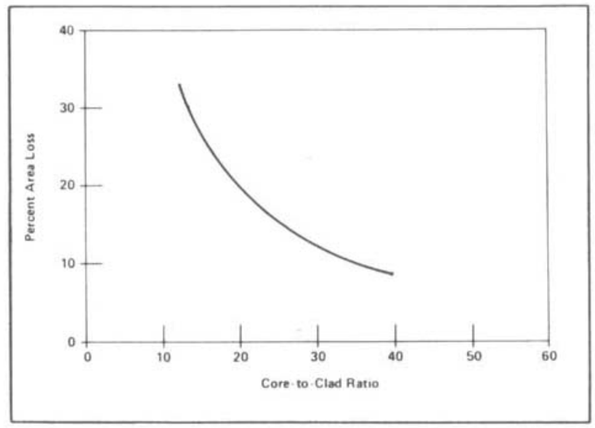

Figure 18 Area Efficiency (Packing Fraction)

generalization may be made: It is not necessary to prevent light interaction between adjacent fibers as long as they do not resonate; it is only necessary to keep the interaction low over an interval of one beat. A fiber immersed in a continuous high-index medium requires a much heavier cladding.

(3) Numerical aperture and incident light distribution determine the fraction of the angular distribution that is transmitted.

(4) Although there will be some absorption or scattering, it is usually negligible in small pieces, except at the ends of the transmission spectrum. In the case of an extramural-absorption mosaic, there is an increase in absorption of image light and a decrease in nominal numerical aperture.

One should be wary of careless experimental measurements of transmission efficiency. Note, for example, that an extramural-absorption mosaic always shows less total transmission than a clear piece having the same numerical aperture, simply because background light has been eliminated; the image itself may well be just as intense, and the contrast may be much improved.

Image Conduit

Single fibers can be fused together to form what are called *multifibers.* Multifibers have essentially the same mechanical properties as single fibers of equivalent dimension; their diameters determine whether they are flexible or rigid. Multifibers are coherent bundles; that is, the relative position of each filament is the same at the input end as at the output end. Filament length and relative position *between* input and output are unimportant because the light they conduct is trapped within the fiber.

* See Glossary for definition.

Multifibers, in turn, can be fused together to form *image conduit,* an actual image carrier. Resolution is limited by the size and packing density of the individual fibers as well as by the care exercised in packing the multifibers. Image conduit has little or no flexibility but can be bent with heat to conform to almost any desired path. The bending radius for a half-inch-square conduit

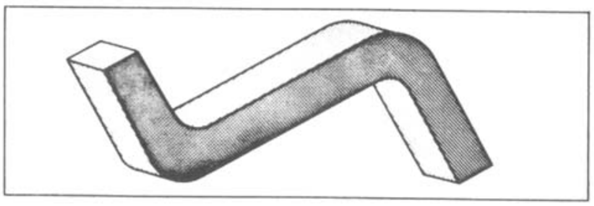

Figure 19 Image Conduit Bending Radius

can be as low as 1 inch (see Figure 19). Image conduit size is limited primarily by cost; segments up to 2 inches square by 2 feet long have been fabricated.

Illuminating image conduit is available that allows a uniform light field to be injected from the side and carried in the direction opposite the image in separate channels or layers (see Figure 20). It serves the function of illuminating objects too close for other types of illumination.

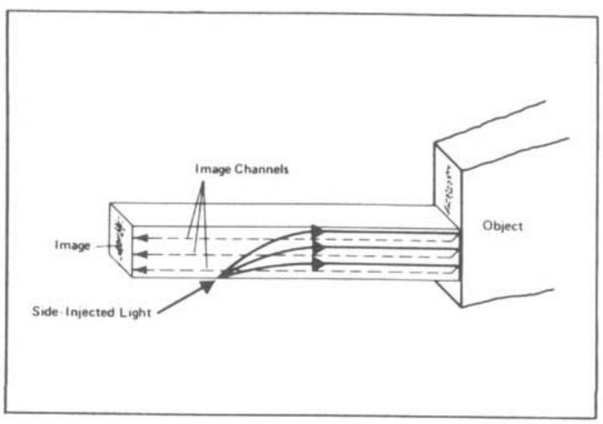

Figure 20 Separate-Channel Illumination

Image conduit can be made with small fiber elements for high resolution. It is inexpensive, rugged, and relatively free from distortion and should be used whenever possible in place of a flexible imagescope.

FACEPLATE

A fiber-optic *faceplate** is an *optical mosaic* in which fibers less than an inch in length are fused together to form a vacuum-tight glass plate. Such a plate is effectively equivalent to a zero-thickness window since the image formed on the inside surface of a vacuum enclosure is transported to the external surface with a minimum loss of light. Because of this basic function, fiber-optic faceplates are frequently used to replace ordinary glass viewing areas in vacuum tube envelopes. They can also be used to advantage for field flattening, distortion correction, ambient light suppression, and control of angular distribution. Common applications include cathode-ray tubes, image intensifiers, storage tubes, and special orthicon and vidicon tubes.

FACEPLATE CONSTRUCTION

Because each application has its own requirements, most faceplates are custom-made. They can be fabricated in any shape into which glass can be machined, including aspheric configurations. Finished plates have been fabricated with diameters up to 12 inches and in strips as large as 1 by 16 inches. Mechanical dimensions are usually held to within ±0.010 inch and can be held to within ±0.001 inch if cost is of no consequence. Plate surfaces are either plano-plano (parallel) or plano-concave; flatness can be kept within a few optical fringes per inch.

The fibers in faceplates range in diameter from 5.5 to 75 microns. Table I lists typical glass types used and their specifications. K-1 and K-2 glass faceplates are not compatible with most photocathode processes but are utilized in phosphor applications; the other glasses are suitable for both. For the majority of current applications, glasses with *numerical apertures* of 1.0 and 0.66 are used.

If intended end use requires any degree of image contrast, faceplates are fabricated with *extramural-absorption* glass, an opaque second *cladding* designed to eliminate unconducted light, thus maintaining contrast and resolution. The amount of such cladding can be varied to conform with plate thickness and contrast requirements.

FACEPLATE CHARACTERISTICS

Image Distortion

Because faceplates are made up of millions of small fibers sealed together under pressure and at a temperature so high that glass becomes slightly viscous, they always present some degree of image distortion. This distortion can be defined in terms of two parameters, shear and gross distortion.

Shear distortion is the displacement or rotation of a small line segment with respect to a perfectly-straight-line image. It is the result of a twist or movement of a *multifiber* relative to those adjacent to it from one surface of the faceplate to the other. Shear distortion is typically 0.002 inch or less for a half-inch-thick plate.

Gross distortion is the apparent bending of a straight line focused on one surface of a faceplate and viewed from the other. It is caused by the gross movement

*See Glossary for definition.

Table I Specifications of Standard Faceplate Materials

Parameter	Glass Type				
	A-10	**H-64**	**K-2**	**D-11/D-15**	**D-14**
Numerical Aperture	0.35	0.66	0.66	0.95	1.0
Fiber Size, microns	15	6-25	6-25	6-25	6-25
Maximum Temperature, °C	500	460	460	525	550
Chemical Stability[a]	Class 1	Class 2	Class 2	Class 1	Class 1
Compatibility[b]	P_c		P	P_c	P_c
Coefficient of Expansion (x 10^{-7}/°C)	89	89	89	89/87	87
90% Spectral Transmission	@ 3200 A	@ 3750 A	@ 3750 A	@ 3900 A	@ 4000 A

[a]Class 1 glass weathers well and will not discolor when heated in a strongly reducing atmosphere. Class 2 glass weathers well but surface discolors slowly when heated in a strongly reducing atmosphere.

[b]°P_C = photocathode;P = phosphor.

of one region of the plate relative to another between the two surfaces. In Figure 21, it is represented by the displacement from an ideally placed straight line at points *A* and *B;* it does not include a uniform axial tilt of the fibers from surface to surface, which would cause a *uniform* displacement of the line. Because gross distortion occurs on more than one axis, its true value is represented by the expression $(D^2_x + D^2_y)^{1/2}$, where D_x and D_y are gross distortions measured at a 90-degree angle from one another. Gross distortion is typically 0.003 inch per 0.500 inch of thickness per inch of diameter.

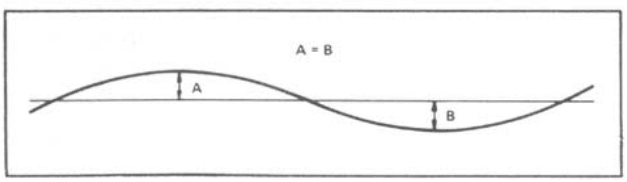

Figure 21 Gross Distortion Schematic

Image Transmission

The *edge response* test can be used to measure image transmission, i.e., contrast and resolution, through a faceplate. The test is performed with a *lambertian* light input, a knife edge, and a collector having a numerical aperture of 1.25 and a slit-aperture *5* microns wide. Typical results for a 6-micron-fiber plate with a numerical aperture of 1.0 are presented in Table II.

Table II Edge Response Test Results

Distance from Knife-Edge Origin (inch)	Percent Response
0.000	<50
0.0005	< 6
0.001	< 3
0.002	< 2.5
0.005	< 0.5
0.010	< 0.2

No direct measure of resolution capability is pro vided by the edge response test, but its readings can be used to derive mathematically a *modulation transfer Junction* curve such as that shown in Figure 22. Sophisticated optical bench systems have been designed to measure modulation transfer function directly, but in their present form they only measure light transmitted in small angles (e.g., numerical aperture = 0.6) and cannot accurately characterize high-numerical-aperture fiber optics. A further limitation of such curves for resolution evaluation is the absence of a fixed cutoff point.

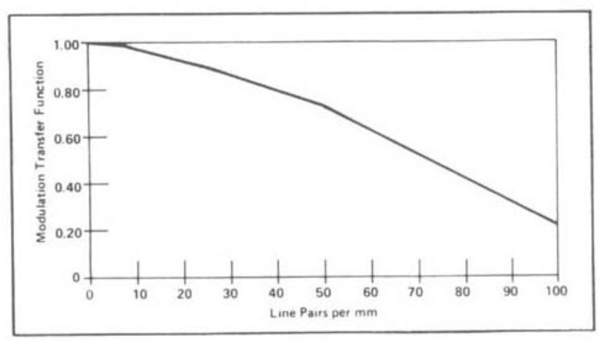

Figure 22 Modulation Transfer Function Curve

VACUUM ENVELOPE FACEPLATES

Expansion

Of the various parameters that enter into the design of fiber-optic faceplates for vacuum tube envelopes, expansion is one of the most critical. A fiber optic is made of two or more glasses (core and cladding) whose coefficients of expansion often differ widely. The glasses used and the ratios in which they are used must be so selected that they closely approximate in expansion the specific glass or metal of which the vacuum tube envelope is made. Average expansion curves for some commonly used materials are shown in Figure 23.

In the temperature range over which-most vacuum tubes are processed, expansion curves normally differ

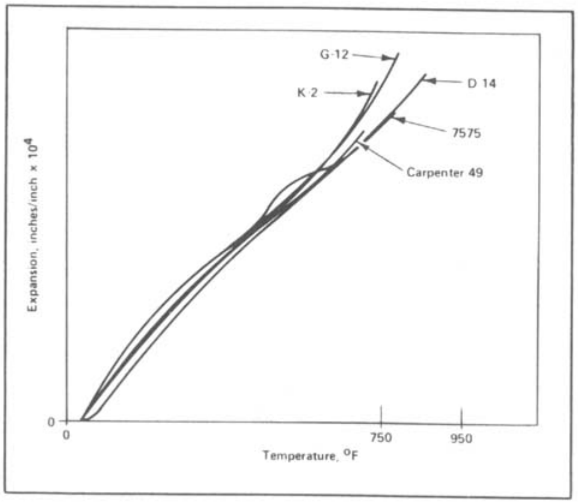

Figure 23 Average Expansion Curves

slightly. This difference is of no consequence in processing tubes 2 inches in diameter or smaller. As the size of the tube increases, however, the expansion differences between the fiber glass, the *frit* used for joining, and the bulb envelope require slower and slower thermal cycles, with the result that a bulb diameter of 7 inches approaches the present maxi mum limit for a glass-to-glass seal.

In systems that require plates up to 1 2 inches in diameter, seal design may incorporate metal flanges (Figure 24) or metal flanges coupled with a gold foil (Figure *25).* During thermal cycling, the gold is malleable enough to flow, relieving any strain due to size differences that may be caused by expansion. The gold link in the seal is adequately strong if handled carefully prior to evacuation; following the clamping action of evacuation, it will withstand light shock and

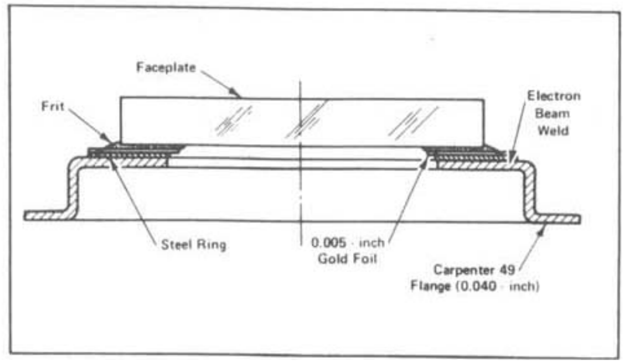

Figure 25 Gold-Foil Seal for Large-Diameter Plates

vibration. The metal-flange and gold-foil techniques add considerably to the expense of making vacuum envelopes but they do, when properly designed, afford methods of manufacturing large bulb sizes.

Where even larger diameters are required, strips up to 16 inches in length can be used if a strip width of approximately 1 inch can be accommodated.

Other Design Considerations

Different vacuum tube applications require different faceplate shapes and sizes. In general, the mechanical pressure caused by the vacuum inside a tube requires a 1: 16 ratio between plate thickness and plate diameter for adequate strength.

Differences in thickness and thermal conductivity, and the resulting variations in response to heating and cooling, must also be considered. Thermal differentials and resultant stresses increase with size. Glass plate with an expansion of 90 x 10-7 inch per inch per degree Centigrade will undergo a stress of 1000 pounds per square inch for each 17-degree-Centigrade temperature increment between its two surfaces. Since the upper limit for safe short-time loading is generally accepted to be 2000 pounds per unit area, the cumulative temperature differential and the loading caused by vacuum become critical factors for large-diameter plates. Both of these factors can be modified somewhat by bulb shape and seal design. Stress can be somewhat relieved either by increasing the seal-edge thickness of the mating parts or by increasing the angle between them by a few degrees.

Fabrication

Parts Preparation

The formation of any glass-to-glass or glass-to-metal vacuum seal requires that the surfaces joined be free of contamination. Fingerprints are the most common offense, since organic materials and salts volatilize

surface contamination is readily made by dry hydrogen firing: any contamination will show up as a non uniform oxide.

Glass parts are neither so readily checked nor so easily cleaned. The cleanest glass surface is a freshly polished one, its only real contaminant being the polishing compound. This polish residue may be removed by washing with detergent in deionized water and then rinsing in clear deionized water. Adherent water should be rapidly removed in a drying oven to prevent surface spotting. Other methods of cleaning glass parts may also be used at the discretion of the operator.

Parts for sealing should not be touched after cleaning except by an operator wearing either cots free of talc or nylon gloves changed frequently enough that body oils do not penetrate to the outside surface. A fired seal free of contamination will be white.

Sealing

Ninety-five percent of the fiber-optic faceplates currently made are of either K-2 or D-14 glass. They are sealed at a temperature of 440 °C for one hour, using Corning 7575 devitrifying frit (ground glass cement) or its equivalent. Methods of frit application include painting, extruding, and dipping.*

After the frit has been allowed to dry, it is hard enough for scraping and may be repaired as required. Scraping at this point determines the position, shape, and thickness of the seal. Care must be taken to remove all frit dust from the optic surface prior to sealing.

Frit sealing requires a fixture that will hold the parts in place and allow them to be forced together. A method of adding weight must be incorporated that will produce a loading of 1 pound per square inch on the seal. Sealing

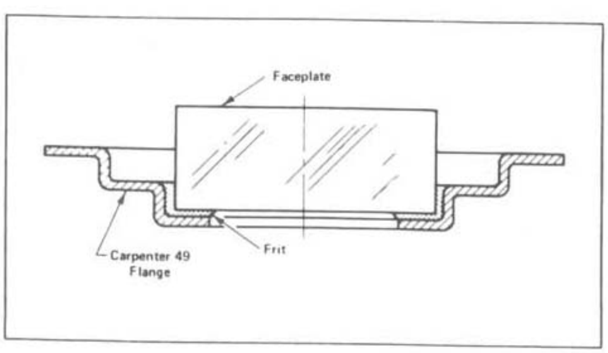

Figure 24 Glass-to-Metal Seal for Large-Diameter Plates

surfaces should be parallel within 0.010 to 0.015 inch. A uniform, fired frit thickness of 0.0 10 inch will result in a strain-free seal; the greater the variation from this thickness, the more unpredictable will be the strength of the seal.

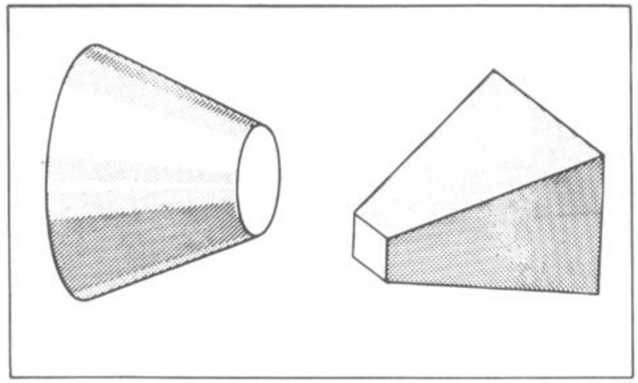

Figure 26 Fiber-Optic Tapers

To aid in control, the expansion characteristics of the fiber optics should be checked periodically, using a dilatometer. The level of stress on the seal area as determined by a polarimeter can be used as a check on the fabrication process itself.

Fiber-Optic Tapers

Tapered image conduit is available in round, square, and hexagonal formats (see Figure 26) and can be fabricated in the form of almost any regularly shaped polygon. The larger end may have a cross section of 1 inch by 1 inch with a ratio between the two ends of up to 40:1. More practical because of manufacturing techniques, however, are tapers having half-inch diameters and ratios ranging from 2: 1 to 10: 1.

Tapers may be used both for the magnification and for the minification of objects. In the process of minification, the speed of an optical system can under certain conditions be increased considerably, making feasible a camera with an f/number of less than 1.

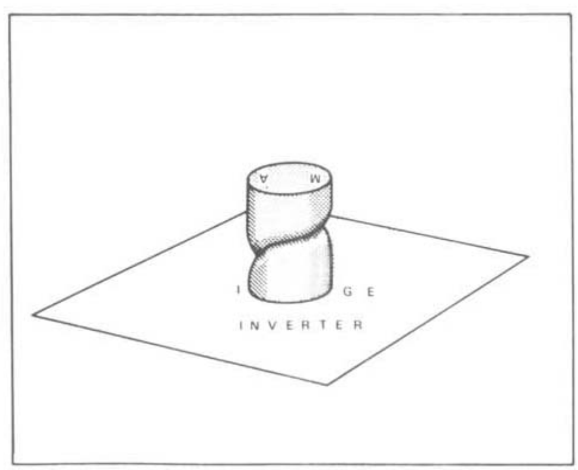

Figure 27 Image Inverter

Image Inverters

An image inverter is a special type of fiber-optic plate by means of which an image can be rotated through any given angle, as illustrated in Figure 27. The advantages of such a device over a lens system include higher speed, compactness, absence of vignetting and lens aberrations, wide control of image rotation angle, and near-elimination of optical realignment caused by thermal expansion. Inverters currently fabricated have diameters of 1 inch. The minimum length is approximately equal to the diameter; i.e., the aspect ratio is about 1:1.

Transmission and resolution characteristics are similar to those of faceplates except that the outer fibers are elongated (a Mae West double taper) and their effective numerical apertures consequently lowered.

*Information concerning frit application and thermal cycling is provided by each vendor for his own frit.

Fibreye™

A fiber optic assembly of rather unique properties can be made which will magnify an image with a great but controlled and highly useful non-linearity, for example, high magnification at the center of the field, and much lower magnification toward the periphery. This device gives a large field of view with large central magnification much in the manner of the human eye providing high foveal resolution, and low peripheral acuity. A substantial range of predetermined magnification shape functions can be accommodated in such assemblies although severe departures from linearity are obtained at the expense of some vignetting of the field. Since the assemblies are substantially solid fused glass structures, they are extremely rugged. Flat curved input/output fields can be accommodated or combined with the *"Fibreye"* function.

In the high center magnification mode, when combined with a fixed focal length lens, the "Fibreye" gives the effect of a zoom lens for moving targets. When the target is small and in the center of the field of view, it is highly magnified as with a telephoto lens. As the target gets closer, it expands to fill the field of view at much less of a rate than with a normal fixed focus lens. This effect tends to keep the target completely in the field of view over a much greater tracking range.

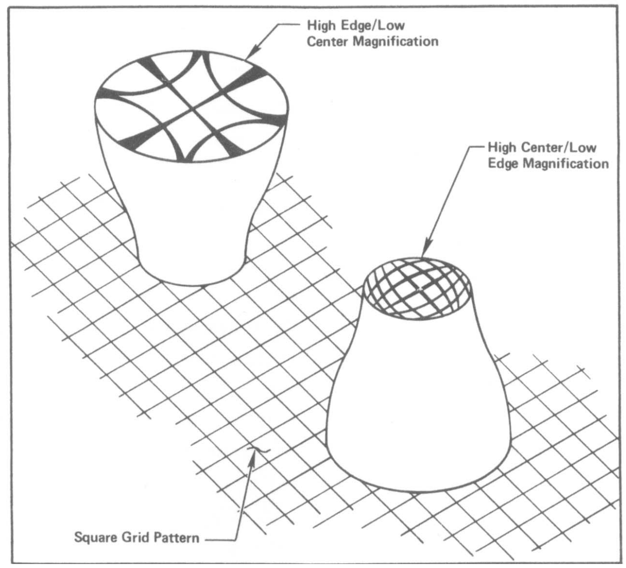

Figure 28 Fibreye

Fibreye is a Trade Mark of the Galileo Electro-Optics Corp. Patent Numbers 4,202,599 and 4,099,833.

GLOSSARY

CLADDING — A sheathing or covering, usually of glass, fused to the core or higher-index material.

COLLIMATED LIGHT — Rays of light traveling as a parallel beam.

CROSS TALK — The observable leakage of light from one fiber to another. The expression is sometimes understood to include light transferred by scattering defects but usually refers only to simple electromagnetic tunneling; it is not normally construed to include light outside the numerical aperture nor light in the webbing, both of which migrate. Cross talk can be eliminated or decreased by increasing cladding thickness, which also increases packing-fraction transmission loss.

DECOLLIMATED LIGHT — Light rays made nonparallel by striae and boundary defects.

DEPTH OF FOCUS — The perpendicular distance from a surface at which an image can be resolved.

DISPERSION — A measure of the change in refractive index with wavelength for a given material. In lens optics, dispersion leads to chromatic aberrations; in fiber optics, it affects only numerical aperture and field angle.

EDGE RESPONSE — A measure of the image resolution and contrast properties of a fiber optics system.

ELECTRON AMPLIFICATION — The multiplication of electrons from a secondary-emission material, caused by a primary electron striking a surface with enough force to dislodge additional electrons.

EXTRAMURAL-ABSORPTION CLADDING — A second cladding of opaque material commonly applied around each fiber in an optical mosaic to absorb light outside the acceptance angle.

FACEPLATE — A group of relatively short, fused optical fibers whose axes are perpendicular to the image surface. Used as an image transport, faceplates are nearly equivalent to a zero-thickness window. They are usually larger than half a square inch.

FRIT — Finely ground glass used to join glass to metal or other glasses. Also called solder glass, it may or may not devitrify (crystallize) during temperature cycles.

f/NUMBER — A number that expresses the light-gathering power of a camera lens system. Mathematically, it has an approximate value of A/Δ, where A is the aperture of a lens and the focal distance. It is also equal to 1/(2N.A.).

IMAGE INVERTER — A fiber-optic device that rotates an image through a predetermined angle such as 180 degrees.

IMAGESCOPE, FLEXIBLE — A fiber-optic image-transfer device that transports an image over long, variable, flexible paths.

LAMBERTIAN SOURCE — A source that looks equally bright from all directions. It emits a flux proportional to the cosine of the angle from the normal.

LIGHT CONDUIT (LIGHT GUIDE) — A flexible, incoherent bundle of fibers used to transmit light.

MAE WEST SYSTEM — A rigid fiber-optic component having one region along its length that is reduced in diameter. It constitutes an effective means of lowering the acceptance angle or numerical aperture of a system.

MERIDIONAL RAY — A ray that passes through the axis of a fiber while being internally reflected (in contrast with a skew ray).

MODULATION TRANSFER FUNCTION — A mathematical expression that reflects the ability of a system to trans port information bits the sizes of which are usually expressed in line pairs per millimeter.

MULTIFIBER — A coherent bundle of fused single fibers that behaves mechanically like a single glass fiber.

NUMERICAL APERTURE (N.A.) — A number that expresses the light-gathering power of a fiber, mathematically equal to the sine of the acceptance cone half-angle. The nominal value may be calculated from the expression $(N^2_2 - N^2_3)^{1/2}$, where N_2 and N_3 are the refractive indices of the core and clad, respectively. The effective numerical aperture is always less than the nominal value since either the resolving power or the transmission must drop drastically as the nominal value is approached. To define an effective numerical aperture, it is necessary to carefully specify a desired operational result.

OPTICAL MOSAIC — A construction in which fibers are grouped and regrouped to build up an area, usually with some degree or type of imperfection developing at the boundaries of the subgroup. When this boundary condition becomes very noticeable, it is called chicken wire.

PACKING FRACTION — The fractional area occupied by core material in an optical mosaic.

RESOLVING POWER — The ability of an optical device to produce separate images of close objects or, more specifically, the maximum number of high-contrast square-edged black and white lines that can be counted with certainty. The latter definition involves a certain amount of subjectivity and is never a complete description of resolution capability. Resolving power is usually measured in optical line pairs per unit length; if television-line units are used, resolving power is numerically twice as great. Except in optical mosaics that are very heavily clad, resolving power falls off as viewing angle approaches the nominal numerical aperture.

SINGLE FIBER — A filament of optical material, glass or plastic, usually drawn with a lower-index cladding.

SKEW RAY — A ray that never intersects the axis of a fiber while being internally reflected (in contrast with a meridional ray).

STRIAE — Spatial variations in the index of refraction in nonhomogeneous glass.

SYMBOLS

A	aperture of lens
d	fiber diameter
d’	resolution diameter
E.M.A.	extramural absorption cladding
I	angle of incidence of light
N	index of refraction
N.A.	numerical aperture
r	resolving power
R	angle of refraction of light
Δ	depth of focus
θ	descriptive angle