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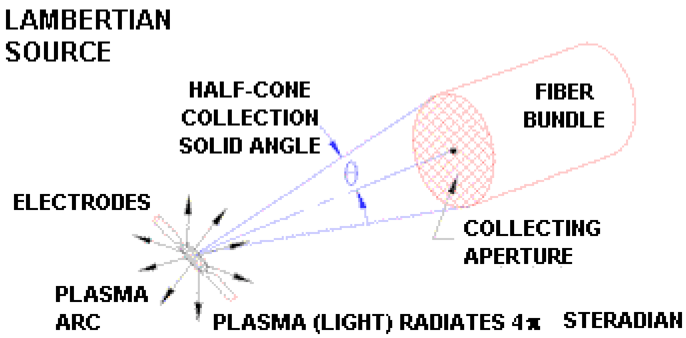
precisely.

Design Considerations for: Optical Coupling of Flashlamps and Fiber Optics

by Robert A. Capobianco



Abstract

High intensity flashlamp source implemented with fiber optics CONDUITS/TRANSMITTERS find application in innumerable areas of technology, particularly in medical analytical instrumentation, machine vision and concentrated spot lighting. Optical coupling seems uncomplicated enough, but for maximum uniformity, stability and energy transfer, with minimum input power, understanding of the principles and techniques involved is paramount for proficient design. Moreover, the mechanical design of the coupling assembly can be a serious consideration especially when convenience and field replacement is a concern. When designing fiber optic systems, common misconceptions and oversights can easily result in consequences of as much as a decade in input power and fabrication complexity/cost. Various techniques and design factors are derived and explained with quantitative results in relation to: plasma size and gradient; flashlamp type (design); and fiber optic parameters which will allow even the novice to converge upon the most efficient/effective design interface for an application. The emphasis here is a comprehensive review of variables, and maximum optical coupling with minimum complexity.

Introduction

Fiber optics technology was introduced into industry a little over a generation ago. Considerable advancements have developed in the last 30 years. There are four major applications that have emerged:

1. image transmission, such as cathode ray faceplates and endoscopes/boroscopes;

2. long range data and signal transmission, i.e. telecommunications;

3. flexible illumination transmission of UV-VIS-IR for medical, machine vision and a variety of lighting tasks;

1. recently as remote detectors for inert high temperature and pressure sensing.

Fiber Optics is a general reference designation, but as employed, may consist of a one inch diameter cable assembly of millimeter sized fibers 4 feet long, or a single fiber 20 kilometers long, or yet, a tapered or straight image transducer 6 inches in diameter and only 1/8 thick. The fibers may be made of glass/silica or plastic having an index of refraction of approximately 1.5 and usually a cladding of less than that but greater than air which is 1.0. Actually, the cladding is unnecessary but it prevents transmission aberrations should the fiber come in contact with other materials in handling.

The fiber or bundle is essentially characterized by:

1. numerical aperture;

2. exponential attenuation as a function of length and wavelength, and of course;

3. diameter.

The numerical aperture or simply NA, is defined by the sine of its maximum half cone angle of acceptance (sinq). Typically, the NA for a fiber optic element may be:

- 0.98 for the faceplate on a CRT, and essentially capable of collecting ± 90° of the phosphor emission for high efficiency contact photographic recording;
- or 0.66 for short distance light applications;
- or 0.44 for sensor deployment;
- or 0.22 for long distance single mode communication.

This dissertation will be limited to only applications involving pseudo-point sources, or more specifically, PerkinElmer Xenon arc/plasma lamps/systems.

How does one couple into a fiber or fiber bundle with maximum energy density transfer from a Lambertian Emitter or simply from any light source?

Hopefully, the shared experience of others may help eliminate plodding through the same errors and misconceptions commonly encountered by many.

Energy transfer is of prime interest, BUT, energy DENSITY is inadvertently misunderstood. The parameter that is often overlooked is magnification - usually because of two reasons; the optical thruput in a lens system is constricted by a remote aperture or by and F*; or the magnification of a reflector system is incalculable or indeterminate, because the source (plasma/arc) is essentially dimensionless without careful, empirical analysis and definition. More simply stated, the plasma - bounded by electrodes - does not emit in a 4p steradian/Lambertian distribution. Also, the angular distribution is more cosine squared than Gaussian. When analyzing/designing a system, the meticulous engineer must think about the peak, halfpower and 10% level of the beam profile, which can vary with wavelength. Simple calculus verifies that the energy transfer/conservation of a lens system is maximum when the magnification is (1) one. Typically, the electrode spacing of arc type lamps is approximately 0.030 to 0.060 inches or 1 to 1½ millimeters. From experience, arc lamps with lesser spacing operate at much reduced efficacies, and arc lamps with larger dimensions operate at greater power but have strike and stability problems.

To reiterate, the practical intent is to transfer maximum light or radiation to the target, AT THE LOWEST COST WITH THE LONGEST LIFE, WITH THE LEAST MAINTENANCE, and with field replaceability. If a lens is employed, an F* in the order of 1.0 is reasonable. Aspherics with an F* of 0.8 are available but are relatively expensive. Condenser combinations (plano convex type - back to back) can be used, but a 4% loss per optical surface must be remembered unless anti-reflection coatings are specified and contended with. In either case, expensive mechanical alignment assemblies become necessary, along with the aggravation of adjustment, compounded with focal length tolerances, aberrations, concentricity, etc. Actually, the angular alignment is far more critical than the XYZ adjustments.

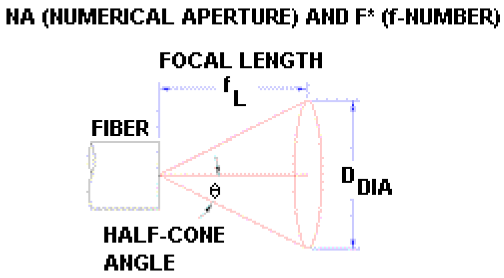
An F* 1.0 optical system collects a half cone angle of arc tan of 0.5 or 26.6°, equivalent to only 0.66 steradian [determined from 4p sin^2 (q/2)] or theoretically only 5.3% of the total 4p steradian. The equivalent F* of a fiber optic element with an NA of 0.66 is F* 0.76, considerably faster than even a double lens element. It is important to understand, that if the system F* is limited by an aperture further along the optical path, then it becomes unnecessary to exceed that F* at the collection input to the fiber/fiber bundle. Except for tolerance margins, why expend the effort and the expense to collect more light at the input if it is to be wasted? The designer should first determine the F* and limiting element in the optical chain; it may be an aperture, a flow cell, a monochromator or perhaps the useful field of view of illumination.

Why use lenses or even reflectors?

Why not abut the fiber/fiber bundle to the arc source (window), i.e. as close as possible? What are the dimensional relationships that govern that effectiveness and realistic efficiency? The following discussion explains that perspective.

When discussing light transfer in simple optical systems, the system NA (numerical aperture) and F (f-number) are often used interchangeably, and are related:*

F* = 1/(2 NA) *E.g.: A fiber bundle with an NA of 0.66 will have the equivalent speed of an F* 0.76 lens - which is quite fast. [Note the relationship between F* and NA as shown in Figure 1.]*



NA = SINq AND F* = f_L / D
WHERE SINq = D / (2f_L) = 1 / (2F *)
OR F* = 1 / (2NA)
E.G. A FIBER BUNDLE WITH NA = 0.66
WILL HAVE THE EQUIVALENT SPEED
OF AN F* 0.76 LENS

Figure 1

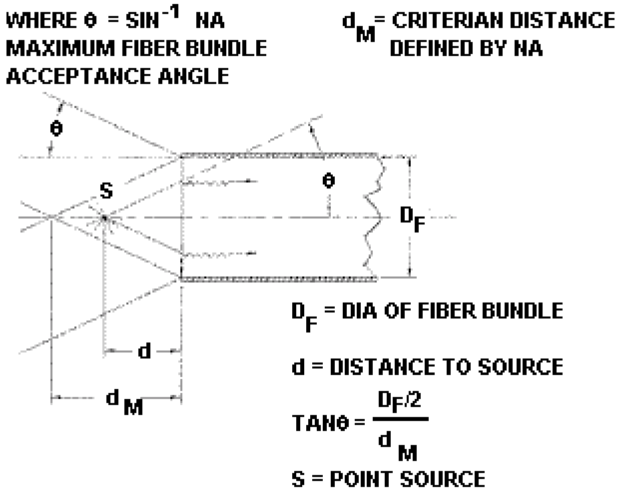


Figure 2

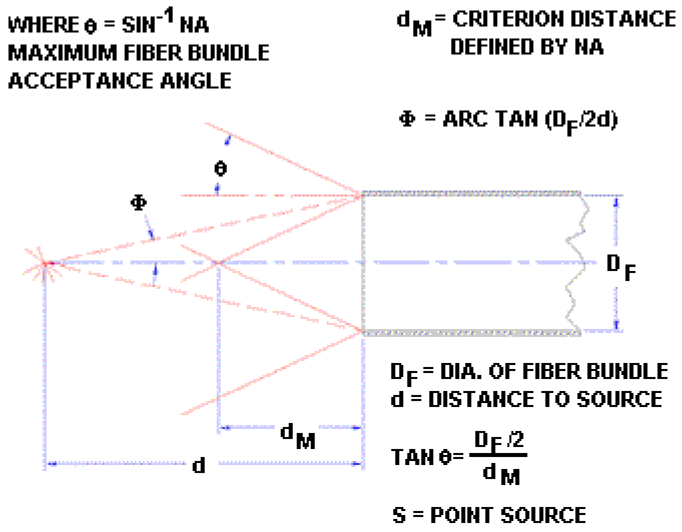


Figure 3

Optical Collection Criteria

Refer to figures 2 and 3 which illustrate the location of a point source in proximity with the input of a fiber bundle or light conduit. In figure 2 the (S) source is located between the dimension d_M and the fiber entrance, and in figure 3 the source is located at a distance greater than d_M. A fiber bundle will only collect a half cone angle of q= arc Sin NA, or less if the source is further away than:

$$d_M = D_F / (2 \tan q)$$

where: Tan q = $(D_F/2)/d_M$;

d is the distance from the source to the fiber entrance; and D_F is the usable diameter of the fiber bundle.

For **NA < 0.4;** $d_M = D_F / (2\ NA)$**;** approximately (i.e. Tan q » Sin q).

For **NA > 0.4;** $d_M = D_F / [2\ Tan(Sin^{-1}\ NA]$ is exact.

Specifically,

for NA = 0.66 0.40 0.22

dM = DF/1.76 DF/0.87 DF/0.45

respectively.

When the distance to the source is < d_M, then, by definition of the NA this is the condition for maximum energy collection (*but not maximum energy density).*

If the source distance is > d_M, then the half cone angle collected from the source is limited by the diameter of the fiber bundle, and the collection efficiency is reduced by;

$$Y = \mathrm{Sin}^2 (F/2) / \mathrm{Sin}^2(q/2)$$
$$\text{whereq} = \text{arc Sin NA}$$
$$\text{and } F = \text{arc Tan}(D_F/2d)$$

The collection efficiency for $d < d_M$,

$$Y \% = [\mathrm{Tan}^{-1} (D_F/2d)(100\%)/\mathrm{Sin}^{-1}\ \mathrm{NA}]$$

The above analysis may be applied quantatatively as a good approximation for sources of a FINITE size where the source diameter (D_S) is less than about 2 times that of the fiber bundle diameter (D_F). Beyond that it is only useful as a proportionality guide. Figures 4 and 5 are an attempt to depict the geometries involved with finite and extended arc/plasmas, or even small linear type flashlamps. Without cluttering this primer with a confuscation of calculus, one can imagine the extended source (S_X) as composed of many segments, each of which is a Lambertian emitter, where only the Cosine Law need be supplied, as long as the extremities subtend the angle defined by the NA (e.g. R_2 and R_3 in figure 5 illustrate lost radiation). The integrity of the relationship is maintained with some derating and from experience will still usually yield better results than a lens coupled design.

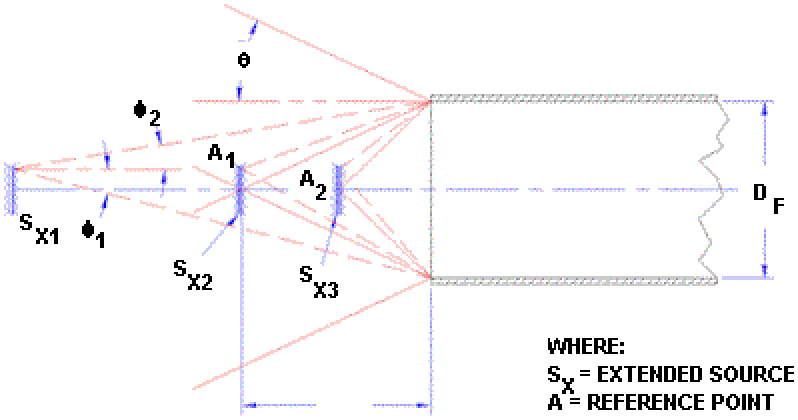


Figure 4

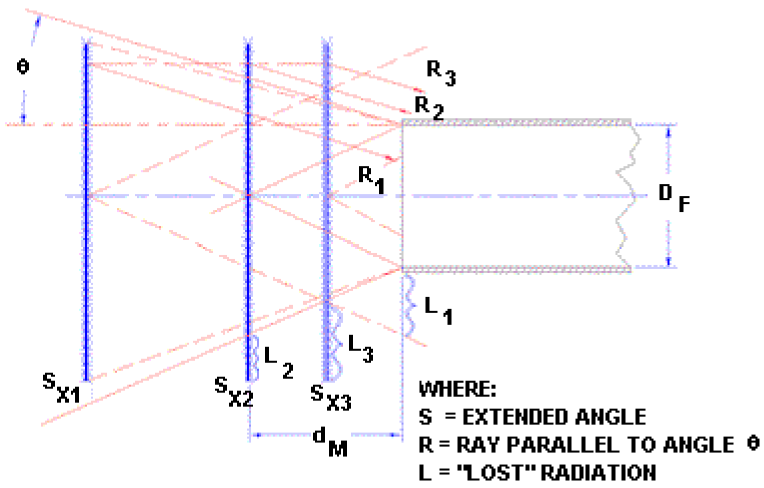


Figure 5

Figure 6 provides a graph of the source to fiber spacing (d_M) required to achieve 100% coupling efficiency as a function of usable fiber diameter (D_F) and the numerical aperture NA. For example, for an 0.5 inch fiber bundle with an NA 0.4 (equivalent F* 1.25) the source must be positioned at or less than 0.57 inch distant to achieve maximum coupling. The curves in figures 7 through 9 were generated to aid in assessing the extent of the coupling loss when the criterion for 100% collection efficiency cannot be met dimensionally; i.e., $d > d_M$. Using the same 0.5 inch diameter and 0.4 NA fiber example, if the fiber head had to be located at a distance of 0.8 inch (instead of 0.6 inch), then a 27% loss can be expected.

D_F = usable fiber bundle diameter

d = distance from source arc to fiber bundle

D_F, d_M, and d must have the same dimensional units

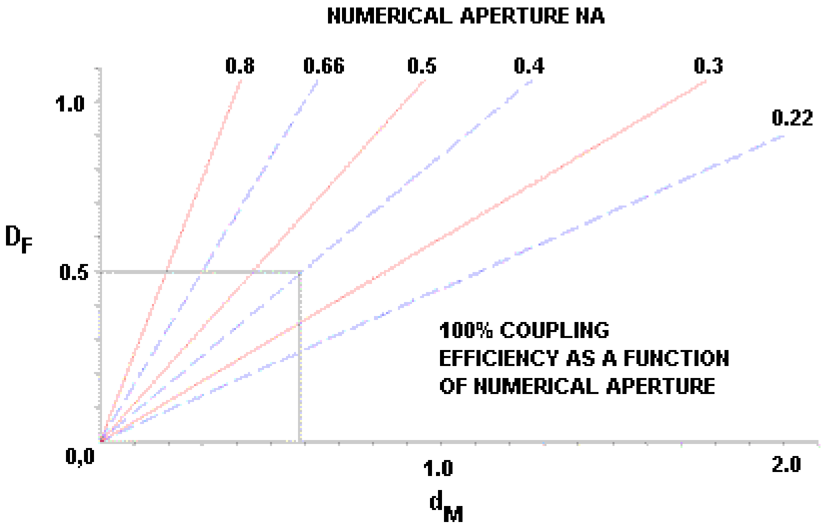


Figure 6

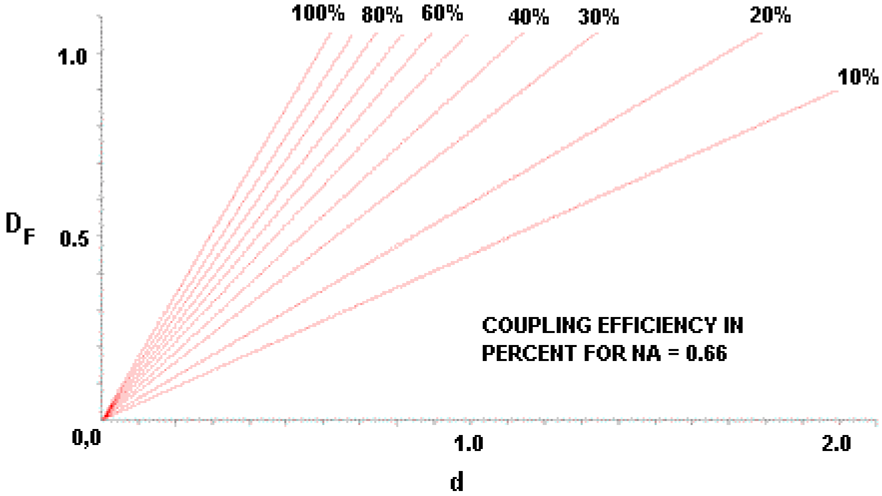


Figure 7

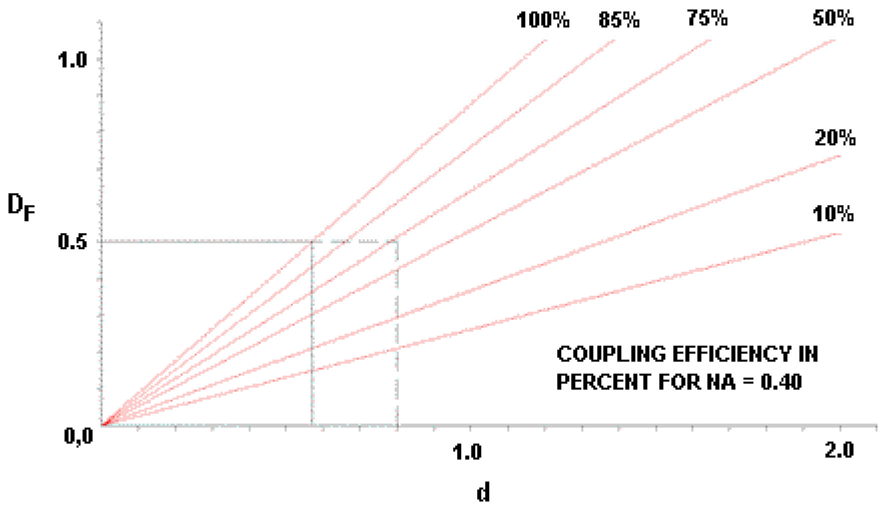


Figure 8

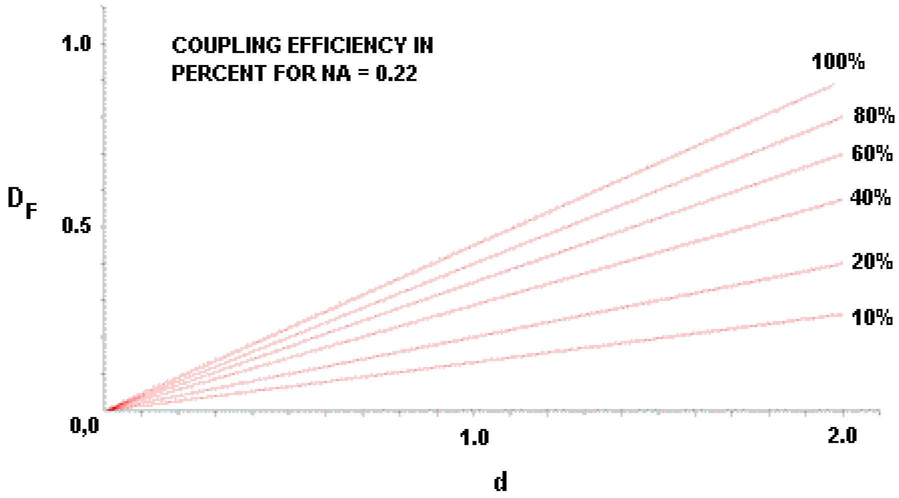


Figure 9

Direct vs. Optical Coupling

Even though the criteria for optimum coupling cannot be met, in most cases, alternative coupling methods (lenses, reflectors, cones) present far greater problems and losses than compromising some parameter which, for example, would be using a higher power or more efficient lamp, or reconsider optimizing the operating conditions. Compare figures 10 and 11.

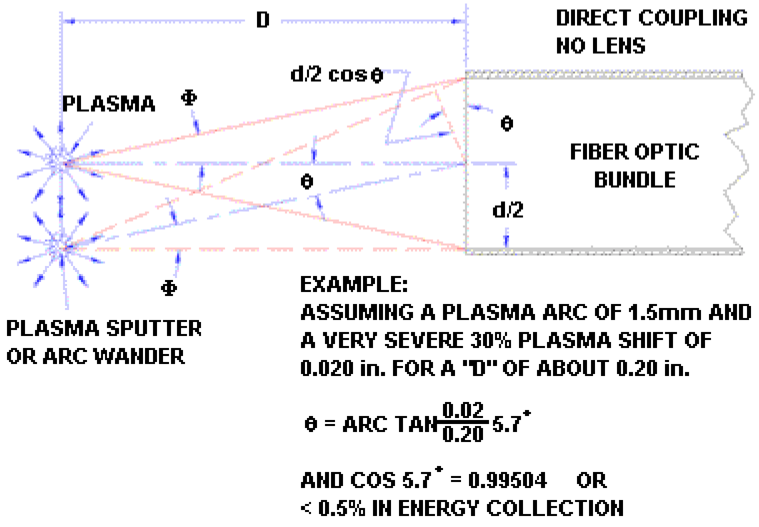


Figure 10

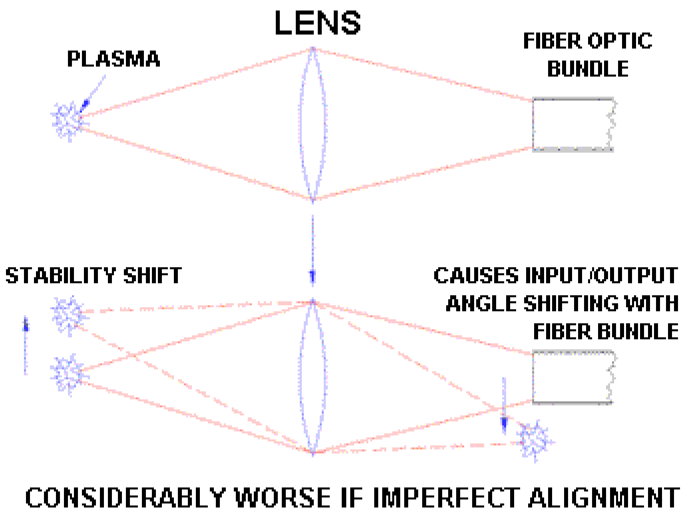


Figure 11

In figure 10, even with rapid severe plasma shifts or arc wander, the collected energy is related to the Cos q and relatively insignificant. In figure 11, the consequence of image shifting is obvious. Aside from critical alignment, other disadvantages with a lens coupled system are that the designer must contend with focal length, concentricity and other tolerances, as well as aberrations, the arc gradient and wandering arc hot spots. Lamp field replacement and realignment can probably be added to the list. The direct coupled lamp is free of all of these concerns. **Depending upon pulse energy and life specifications, custom bulb lamps can be fabricated with the electrodes very close to the glass envelope to reduce d_M to a minimum.** Typically, the arc center is located 0.2 to 0.3 inch from the exiting glass window, which is usually 1mm to 2mm thick. As an example, for subtended half-cone collection angles from 10° to 40°, it may be shown by the ratio of the solid angles $\sin^2(q/2)$, that **for an arc-to-fiber spacing reduction of 2, an increase in radiation collection can amount to a factor as much as 4 to 8.** From experience, the diligent system designer can almost always find some parameter which will allow a reasonable increase in energy thruput either by altering the optical path, or pursuing a custom lamp, or whatever, meaning, one should endeavor almost anything which will eliminate the lenses and allow direct coupling.

Integrated Reflector Lamps

Flashlamps that have parabolic, ellipsoidal and spherical reflectors fabricated internal to the lamp, and with the arc located at a focal point are available. In the sperical design, such as the PerkinElmer High-Stability FX-1160 Series, the reflector is positioned at the rear of transverse electrodes with its radius of curvature exactly coincident with the arc center; thus the rear directed radiation is returned back through a transparent plasma and adds to the forward light emission. A second important advantage of this design is that the optical noise ordinarily encountered and caused by the back scattered light is eliminated. The disadvantages of this design are none. This is not so with the parabolic and ellipsoid designs in which axial electrodes interfere with emission and the angular distribution of the output beam profile, as well as magnify the spatial distribution. Integrated ellipsoid and paraboloids have been employed in (very) high intensity CW metal-ceramic lamps for some time, and are quite effective as a brute force method of pumping intense light into small fibers in the order of 5mm and less. *Further discussion in this area is beyond the scope intended for this introductory primer, and will be the subject of a second paper.*

Some other considerations important to the systems designer which constantly raise questions are:

GRIN Lenses

GRIN lenses may have utility in applications where space is limited. A GRIN lens is a GRaded INdex rod type lens which may offer an advantage in that they are a simple one piece element, chromatically aberration corrected, polarization preserved, one piece element, and allow more design flexibility. They can form real images and obey the same rules for magnification and energy transfer as conventional lenses, but are compact (typically 1 to 3 mm in diameter). The transmission of a GRIN lens may be from 90% to 98% depending upon the selection of anti-reflection coating; however, they are generally wavelength limited to a spectral range of 380 nm to 2 microns. They are often employed effectively as coupling and condensing lenses for fiber optic elements, and as relay lenses for small diameter imaging systems such as rigid and flexible fiber endoscopes and boroscopes.

UV Fibers

Ultraviolet fiber bundles or light pipes are readily available and operate with the same principle of total internal reflection. Generally they are quartz fibers and have a useful transmission range from 200 nm to 1200 nm. They are especially facilitating in coupling UV sources (usually large and cumbersome) to inaccessible targets. Transmission typically varies between 20% and 65% in the 200 nm to 400 nm spectral range, but the designer must be aware that the NA (numerical aperture) will vary considerably with wavelength and somewhat with fiber length. For example, the exit angle of the UV light pipe at 250 nm may be only ½ that of the exit angle at 550 nm.

Diffraction Errors

When designing with collective or coherent fiber optic bundles composed of micron sized fibers, diffraction and mode propagation may cause disconcerting unpredictable effects in beam distribution at the exit end. A detailed analysis is beyond the scope of this paper, but an example will suffice to alert the designer. Angular beam spread due to diffraction is given by

$$\text{Sin } q = l/D$$

where q is the half cone angle and D is the diameter of the individual fiber in the bundle. As an example, consider a bundle consisting of 4 micron fibers transmitting light at 550 nm and at 1.0 micron.

$$\text{Sin } q = 0.55/4 \text{ and } 1.0/4,$$

$$\text{then, } q = 7.9^\circ \text{ and } 14.5^\circ \text{ respectively}$$

Since q is the half cone angle, the total spread of the exiting annular ring will be as much as 16° and 29° respectively, which can result in a significant error in analyzing energy density transfer and the NA of the source beam. It is important to note that the angular spread is a linear function of wavelength.