Practical LEOS Applications

M. Leonard Riaziat, Associate Editor

Coupling Light from Incoherent Sources to Optical Waveguides

by Loren F. Stokes

Spatially coherent laser light can be coupled into an optical waveguide with nearly 100 percent efficiency. However, coupling light from a spatially *incoherent* source to a waveguide can be frustrating. A source emitting visible light may be very bright to the eye, but only a small amount of optical power will be coupled into the waveguide. For example, the source may be emitting 1 watt of optical power, while perhaps 1 microwatt is coupled. A common reaction is, "I must be able to improve this result with better optics." However, thermodynamics limits the maximum amount of optical power one can couple from an incoherent source, so that no amount of engineering sophistication can secure an increase. On the other hand, in many cases only a very simple imaging system is required to couple the power that is available.

In the following discussion, the term *incoherent* applies to spatial incoherence (versus temporal incoherence), while *modes* refers to spatial or transverse modes (versus longitudinal or frequency modes). We then describe how to efficiently couple blackbody radiation to optical fiber waveguides. The same basic principles hold for other types of waveguides, such as integrated optic waveguides. Radiation emitted from other types of extended sources, such as surface emitting LEDs or ionized gases, can be efficiently coupled to waveguides using the same techniques.

Blackbody Radiation

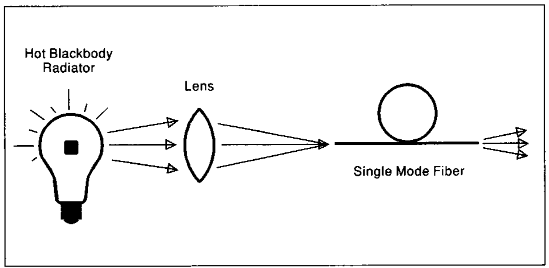
A very simple example of coupling an incoherent source to an optical waveguide illustrates the basic principles. Consider a hot blackbody radiator that is emitting light over an extended surface area. The intensity, I, (power per unit area) per unit wavelength, λ emitted from a blackbody radiator of emissivity ε at temperature T (degrees Kelvin) is given by the Planck Radiation Law:

$$\frac{dI}{d\lambda} = \frac{\varepsilon\, 2\pi c^2 h}{\lambda^5} \frac{1}{e^{(hc/\lambda kT)} - 1}$$

where h is Planck's constant, k is Boltzmann's constant, and c is the speed of light. Assume the blackbody is tungsten at 3000 K. At 1300 nm, $\varepsilon = 0.33$, and we have $dI/d\lambda = 85\ \mathrm{mW/cm^2/nm}$. Incidentally, at 3000 K, the blackbody has a peak emission wavelength of 960 nm.

How much of this rather large optical power can be coupled to an optical fiber waveguide? We can estimate the coupled power without knowledge of the detailed mode structure of the optical fiber. We cannot butt the fiber end to the hot tungsten, because the fiber would melt. However, we can simply image the surface of the tungsten onto the end of the optical fiber using a positive lens (Fig. 1.) Furthermore, let the object and image distances be equal, giving unity magnification. This positioning will image a fiber core-sized area of the tungsten surface onto the fiber core. The common single mode fiber used in 1300 and 1550 nm wavelength telecommunications has an approximate core diameter of 9 μm and a core area of $6 \times 10^{-7}\ \mathrm{cm}^2$. About 50 nW/nm is emitted at 1300 nm from the core-sized area of the filament. The fiber acceptance angle, which is related to the numerical aperture, is approximately 0.1 radians, while the tungsten surface radiates into a 2π steradian half space. Thus, only on the order of one percent of the 50 nW/nm can be guided by the single-mode fiber. That value represents a power spectral density of about 0.5 nW/nm (or -63 dBm/nm), assuming that numerical aperture is limited by the fiber rather than the lens.

The Thermodynamic Limit



1. Unity magnification imaging of a blackbody radiator to a single mode fiber.

It is not possible to increase the incoherent power coupled to the optical fiber by using a more sophisticated imaging system. A passive optical system (lenses, mirrors, etc.) cannot increase the radiance (radiated optical power/unit area/unit solid angle) of a source. For example, changing the magnification of the lens system in Fig. 1 from 1 to 0.5 would image an 18 μ m diameter spot of the tungsten surface onto the 9 μm fiber core. This change will increase the intensity of light incident on the fiber core by a factor of four, but the divergence solid angle will simultaneously increase by four. Therefore, the radiance is constant, and there is no change in power coupled to a fiber waveguide having a fixed acceptance angle. A lens system with unity magnification, and a lens having a numerical aperture at least as large as that of the fiber, is a simple system that works as well as any. The object/image distance can be any value that is convenient, and this approach is equivalent to butting the fiber end to the surface of the radiator.

A lens cannot increase the radiance of a source, as inferred from basic thermodynamic laws [1]. Consider an absorber attached to the output end of the fiber in the Figure, and let the lens and fiber have very large numerical apertures such that most of the radiation emitted from the blackbody area near the lens axis is captured by the lens and guided by the fiber. The absorber is heated to a temperature, T_a, where its own radiated power equals its absorbed power. If the lens could increase radiance, then more power per unit area could strike the absorber than would radiate from the blackbody. Therefore, T_a could be greater than T, the temperature of the blackbody. If this were the case, then the efficiency of extracting work from the heat energy of the absorber would be greater than the efficiency of extracting work from the heat energy of the blackbody radiator itself. This behavior would violate the second law of thermodynamics. Therefore, T_a cannot be higher than T, and the lens cannot increase radiance.

Nonimaging Optics

Nonimaging concentrators are used to collect and intensify light more efficiently than lenses and mirrors [2]. One example is a compound parabolic trough used to concentrate the sun's energy onto an absorber tube. All rays of light should strike the absorber tube, but an image of the sun is unimportant. Nonimaging optics still must obey the second law of thermodynamics. The radiance generated in a solar collector cannot exceed the radiance on the surface of the sun. There is one loophole, however. If the concentrator is made of a material having a refractive index n, the radiance can be n^2 times that of the source. Reference 2 describes an experiment where concentrated sunlight radiance exceeded the radiance on the sun's surface by 15 percent. However, such devices utilize very large numerical apertures and are not appropriate for coupling to (relatively) low numerical aperture waveguides. Stated another way, an absorber of sunlight has a very large acceptance angle and, unlike the waveguide, can benefit from a large numerical aperture system.

Modal Description of Blackbody Radiation

The estimate of 0.5 nW/nm power spectral density at 1300 nm wavelength coupled into a single mode fiber waveguide did not incorporate the modal nature of the waveguide. The guided mode has a specific intensity distribution, while the waveguide is illuminated uniformly. For our case, a more relevant description of blackbody radiation is found in the blackbody power spectral density (power per unit frequency) per spatial mode, dP/dν [3]

$$\frac{dP}{d\nu} = \frac{\varepsilon h\nu}{e^{h\nu/kT} - 1}$$

where ν is the optical frequency. The term hν in the numerator is the photon energy and represents one photon of noise per mode. Neglecting the factor of -1, the denominator is the Maxwell-Boltzmann distribution of such photons at temperature T. A blackbody radiator thus radiates in many spatial modes, each one distinguishable and physically separable. The optical fiber waveguide is illuminated with light in many spatial modes, but only the guided ones propagate.

Again, we take $T = 3000$ K, $\varepsilon = 0.33$, and $\nu = c/\lambda = 231$ THz ($\lambda = 1300$ nm). Let $d\nu = 178$ GHz for a 1 nm optical bandwidth. We calculate $dP = 0.23$ nW. Thus the power spectral density per spatial mode is 0.23 nW/nm. A "single mode" fiber waveguide actually supports two modes with the same intensity distribution but orthogonally polarized, so the actual power spectral density in the waveguide is 0.46 nW/nm (or -63.4 dBm/nm). The earlier estimate of 0.5 nW/nm was quite accurate!

Once we have achieved this amount of coupling to the single mode fiber, we need not bother to optimize the coupling optics any further. The only way to increase the coupled power is to raise the temperature of the blackbody source. The diameter of the fiber can be increased for greater coupling, but at the expense of single-mode behavior.

In many applications, single mode fibers are not needed. Of the commonly used multimode fibers, two graded index types are popular. One has a 50 µm core diameter and 0.20 numerical aperture, while the other has a 62.5 µm core diameter and 0.275 numerical aperture. These fibers support 290 and 860 spatial modes, respectively, including both polarizations [4]. Using the power spectral density of 0.23 nW/nm per mode at 1300 nm wavelength, we conclude we can couple 67 nW/nm (or -41.7 dBm/nm) into the 50 µm core fiber, and about 200 nW/nm (or -37.0 dBm/nm) into the 62.5 um core fiber. Again, once we achieve close to this coupling for a blackbody source at 3000 K, we need not try to do better.

Applications

Such low levels of optical power are useful because of the tremendous sensitivity of optical receivers. A well designed optical receiver with a 10 Hz bandwidth has a noise level of about 0.3 picowatt (or -95 dBm) of optical power. If a 10 nm wide bandpass filter, centered at 1300 nm, is placed between the lens and fiber end as shown in the Figure, up to -53 dBm of optical power could be coupled into the single mode fiber. The signal-to-noise ratio would be 42 dB, which is more than sufficient for measurement applications. For example, if the bandpass filter is wavelength tunable, such as a monochromator, optical measurements versus wavelength can be easily performed.

Acknowledgment

I wish to thank William R. Trutna, Jr. of Hewlett-Packard Laboratories for insight and numerous discussions relating to this work.

Loren F. Stokes [M] is a member of the technical staff at Hewlett-Packard Co., Lightwave Operation, in Santa Rosa, California.

References

1. D. H. McMahon, "Efficiency limitations imposed by thermodynamics on optical coupling in fiber-optic data links," *J. Optical Society of America* **65**, p. 1479, 1975.

2. R. Winston, "Nonimaging Optics," *Scientific American*, March 1991, p 76.

3. A. E. Siegman, *An Introduction to Lasers and Masers*. New York: McGraw-Hill, 1971.

4. J. C. Palais, *Fiber Optic Communications*, 2nd Ed. New Jersey: Prentice Hall, 1988.