Fiberoptic Tapers in High-Resolution Scientific Imaging

What you need to know when selecting a fiberoptically coupled CCD camera

Figure 1. *Princeton Instruments PI·SCX™ fiberoptically coupled CCD camera.*

Figure 2. *Photometrics XR·300™ fiberoptically coupled CCD camera.*

Introduction

More and more frequently, researchers and industrial engineers are utilizing fiberoptic tapers to enlarge or reduce digital images. X-ray crystallography, nondestructive testing (NDT), x-ray high-resolution imaging, medical and dental radiography, electron imaging, and streak tube readout are just a few examples of the applications for which fiberoptic tapers are well suited.

Manufacturing Process

A fiberoptic taper is a bundle of optical fibers formed by a stretching process from a fused block, or *boule*, of parallel fibers. This boule is created through a series of fiber-drawing and assembly operations followed by a fusing or pressing operation that first welds single fibers together, then bundles the fibers (creating multifiber bundles), and finally welds the multifiber bundles (forming multi-multifiber bundles).

Next, the boule is machined to the required round cross section and tapered in a customized machine that heats and stretches it in a precisely controlled manner in order to minimize distortion. The resultant piece, which is hourglass-shaped and symmetrical, is cut into two tapers. Lastly, the end faces are ground and polished, either flat or curved, depending on the application and the topography of the mating surfaces.

CCDs and Fiberoptic Tapers

A fiberoptic taper's image magnification is the ratio of the large and small ends' diameters. Because light can pass through a taper in either direction, it functions equally well as a magnifier or a minifier. Since image transfer occurs from one face to the other, a fiberoptic taper can be coupled to other components, such as an image-intensifier tube, a streak tube, or a CCD (charge-coupled device). **See Figures 1 and 2**.

In fact, when compared to a lens/mirror-based CCD camera system, direct coupling of the light source and the CCD via image-preserving fiberoptics yields significant gains in the amount of light collected. For example, a fiberoptic taper with a demagnification ratio of 2:1 has a collection efficiency 16 times greater than that of an f/1.2 lens **(see Figure 3)**.

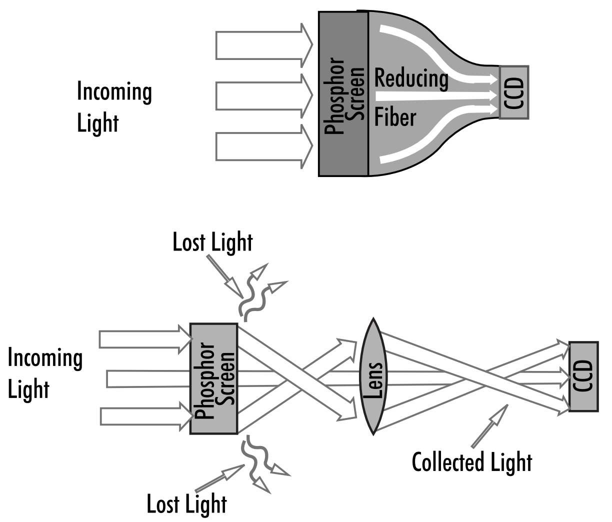


Figure 3. Fiberoptically coupled CCD cameras (top) have a significantly higher collection efficiency than comparable lens-coupled CCD cameras (bottom). The fiberoptic taper, with its larger light-capturing area, maintains the incident pattern of illumination and delivers it to the CCD.

Properties

An individual taper, whether large or small, contains millions of individually clad optical fibers that allow the taper to transmit ultra-high-fidelity images. Each of the taper's many fibers carries an elemental portion of the image; this elemental portion corresponds to part of a single pixel in a CCD. Note that it is very important to have a sufficient number of fibers per pixel in order to preserve the high-resolution performance possible with a CCD. The recommended minimum is nine fibers per pixel. If the number of fibers per pixel drops below four, there can be an adverse effect on resolution.

In order to maximize light transmission through the fiberoptic, individual fibers are clad to contain light by total internal reflection. For ultra-high-resolution imaging applications where fibers of 3-4 μm (small-end diameter) are desired, the ratio of core glass diameter to cladding diameter approaches 50%.

When light enters a fiber at an angle steeper than the total internal refection angle, it will "leak" into the cladding. To maintain high contrast, a stray-light absorber, generally referred to as EMA (extramural absorption), is added to the fiberoptic taper to control stray light that either enters through the cladding or escapes from the glass fibers. Manufacturers implement several different types of designs, including interstitial, statistical, annular, and end-blocking contrast-enhancement EMAs **(see Figure 4)**.

Numerical Aperture

Numerical aperture (NA) is a measure of the maximum incidence angle at which light rays will be transmitted down a taper by total internal reflection. NA is a function of the refractive indices of the cladding glasses and the core.

As light travels down a fiber, it strikes the inside of the fiber wall numerous times. When the fiber is being utilized as a minifier, each successive reflection changes the angle of incidence, which becomes steeper as light moves from the fiber's large end to its small end. Eventually, the critical angle for total internal reflection is surpassed. At this point, light begins to "leak" out of the core glass into the cladding. In effect, loss of light after many reflections reduces the overall NA of fiber tapers. The *effective* NA of a tapered fiber has a simple relationship to the fiber's geometry — it is the fiber's maximum NA multiplied by the ratio of the taper's small-end diameter to its large-end diameter.

The effective NA of the taper establishes the limit of the taper's overall transmission abilities. Any light entering beyond this angle simply escapes through the fiber walls while traveling down the taper and is subsequently absorbed by the EMA. This is why the large end of a taper appears black when viewed from an angle beyond the maximum incidence angle.

$$NA_{eff} = NA_{max} * D_{min} / D$$

D_{min} = *smallest diameter*

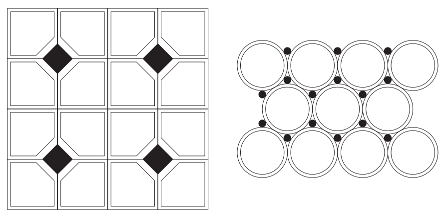
D = *larger diameter*

$NA_{max} = \sqrt{n_1^2 - n_2^2}$

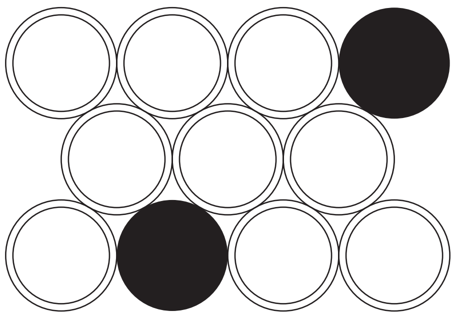
n_1 = *index of refraction of core (typically 1.81)*

n_2 = *index of refraction of cladding (typically 1.52)*

(a)



(b)



(c)

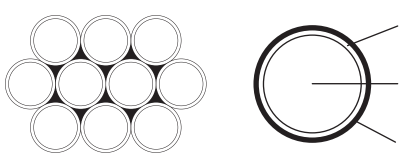


Figure 4. *Examples of (a) interstitial, (b) statistical, and (c) annular EMA.*

Unless otherwise specified, modern tapers are made with glasses that are chosen to provide a relatively high NA (typically 1.0). Light in this NA departs the small end of the taper with a spread of 180 degrees. Therefore, to minimize loss of resolution, it is crucial that the taper be coupled very closely to another component, such as a CCD. Roper Scientific™ uses a patented process (US Patent 5,134,680) to profile tapers to match the curvature of the CCD, thus preserving the highest resolution possible. Fiberoptic tapers can be bonded to most front-illuminated CCDs as well as some back-illuminated devices.

Transmission

Additional factors contributing to the transmission abilities of a taper include the internal transmittance of the core glass, which is a wavelength-dependent characteristic, the area of the core relative to the area of the overall fiber (core ratio), and the reflection from the end faces. Reflection losses can be reduced by coating the end faces with an antireflection coating.

For collimated light:

$$T_{COLL} \cong T_{CORE} \times C_R \times (1 - R)^2$$

For Lambertian (diffuse) light (typical phosphor):

$$T_{LAMB} \cong T_{COLL} \times (NA_{eff})^2$$

T_{CORE} = transmittance of core glass
C_R = core-to-cladding area ratio
R = reflection at each end face

Typical values:

T_{CORE}: 0.98 / inch @ 600 nm
0.55 / inch @ 400 nm

C_R: 0.5 - 0.75

R: 0.04 - 0.09 (depends on the index of refraction)

The core ratio depends on the size of the fibers at the small end of the taper. If they are larger than 5 μm, a core ratio of 0.75 is generally employed. A core ratio of 0.5 is used if they are as small as 2.5 μm.

Resolution

The image resolution of a taper is largely a function of the fiber size. It is generally expressed in terms of the limiting resolution (in lp/mm) and is different at both ends. A useful method for calculating the resolution of a taper is to divide 500 by the fiber diameter measured in mm. For instance, a fiber size of 10 μm implies a resolution of approximately 50 lp/mm.

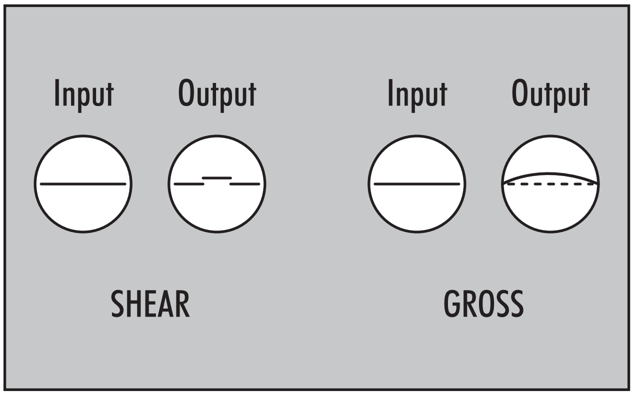


Figure 5. *Shear distortion and gross distortion.*

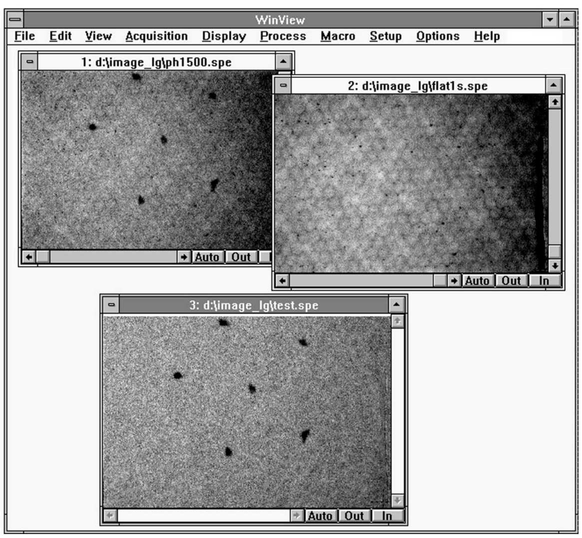


Figure 6. *Image flat-fielding. An image created using a uniform-intensity light source (upper right) is utilized to correct for nonuniformities caused by a fiberoptic taper. The final version of this mammography phantom target shows no trace of the pattern.*

Distortions and Blemishes

The primary disadvantage of fiberoptic tapers is the inherent presence of distortions and blemishes that are introduced during manufacture. Although the process for making tapers has improved over the years and is designed to minimize distortion, it still involves the flow of softened glass and thus absolute uniformity is not realistic. Tapers can have spot blemishes (burned or broken fibers), line blemishes (chicken wire), and various image distortions (termed shear and gross). **See Figure 5**.

A spot blemish is defined as a small area with reduced or no transmission, while a line blemish is defined as a pattern of dark fibers two to four fibers wide at the multi-multifiber boundary. A shear distortion, which is also introduced at the time of fusing multi-multifiber bundles, is defined as a lateral displacement that causes a straight line to be imaged as a broken line. A gross distortion is defined as a distortion that causes a straight line to be imaged as a continuous curve. A gross distortion is often more pronounced in a short taper, where the glass changes shape abruptly, sometimes resulting in the formation of a slight barrel or pincushion distortion.

New materials and manufacturing processes can lessen some of these effects, however. For example, a new fiber-drawing process has been developed that minimizes shear distortions and spot blemishes for tapers as large as 50 mm in diameter. A number of software acquisition and processing techniques can also be employed to offset minor taper flaws, such as flat-fielding to eliminate the chicken wire effect by compensating for any nonuniformities in pixel-to-pixel responsivity **(see Figure 6)** and distortion-correction algorithms to eliminate barrel and pincushion distortions.

When manufacturing high-performance fiberoptically coupled CCD camera systems, Roper Scientific only uses the highest-quality tapers that are free from major distortions and blemishes. When evaluating digital imaging solutions, it should be kept in mind that the presence of inherent minor flaws associated with tapers is almost always outweighed by the superior light-collection efficiency offered by these fiberoptically coupled CCD cameras systems.

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