Optical system requirements for laser scanning systems

By Robert E. Hopkins

The November 1986 issue of *Optics News* featured an overall review of laser scanners in Leo Beiser's article "Imaging with laser scanners." In that article, Beiser assigned low, medium, and high performance levels to scanners based on the number of addressable elements (pixels). This article concentrates on the optics associated with laser scanners, in particular medium and high performance devices.

Currently, the optical systems for the medium level and high level scanners are capable of imaging from 2,000 to 80,000 pixels for each scan line. Scanning speeds are increasing, with a trend to 10M pixels/per sec. To support these large information transfer systems, polygon or holographic scanners appear to offer the only acceptable choices. The following discussion of optical requirements reflects the author's experience with these two types of scanners. The sample designs included are close to the current boundaries to expect in scanning lenses.

Special optical requirements for high resolution laser scanners

The three types of optical systems for scanning a laser beam using a deflection device are called post-objective, pre-objective, and retro-focus scanning.[1,2]

Post-objective scanning has a major advantage over pre-objective, for the lens can work on axis. The lens can be a simple plano convex lens for many applications. For high resolutions it can be fully corrected, for spherical, coma, and chromatic aberration, to large numerical apertures. The disadvantage of this method is that the material to be scanned has to be on a curved surface.

Pre-objective scanning requires flat field lenses. Since the scanning element is in front of the lens, these objectives are different from photographic lenses, which have their aperture located inside the lens. The scanning element is the entrance pupil for the lens and there must be space to allow clearance between the glass of the first lens and the scanning element.

Retro-focus scanning allows compact systems. The feed beam is introduced from just beyond one end of the scan line. It is collimated as it passes through the lens and then is redirected back through the lens at the angle determined by the mirror. This system is not quite as symmetrical as it appears, for the feed beam always comes in from the edge of the lenses operating field. Any aberrations on this beam are added to the aberrations for all the field angles in the scan. One can not assume that the double pass will correct all the coma and distortion errors.

When the scanning element and the lens are fixed in relation to each other and are rotated together about the optical axis of the incident laser beam, simple lenses can be used as either pre- or post-scanning lenses. The scanning spot scans a complete circle on the inside of a tube. This is an ideal system for inspecting the inside surface of a tube. Documents can be inserted on the inside of the tube and scanned by translation of the tube. In this mode of scanning, it is best to place the lens after the turning mirror, for then the centering of the lens is not as critical.

Most of the systems currently being developed appear to be using post-objective scanning requiring flat field lenses. The following special conditions must be considered during the design of these lenses:

- **The F-θ *condition***

To maintain a uniform exposure to the material being scanned, the light spot must scan at a uniform velocity. The polygon or the holographic element run at uniform speed so the beam sweeps at a constant angular velocity. The image positions on the scan line are then uniformly spaced. To meet this condition, the lens image height should be proportional to the scan angle. This is called the F-θ condition for a scan lens.

For a normal zero-distortion lens, the image position on

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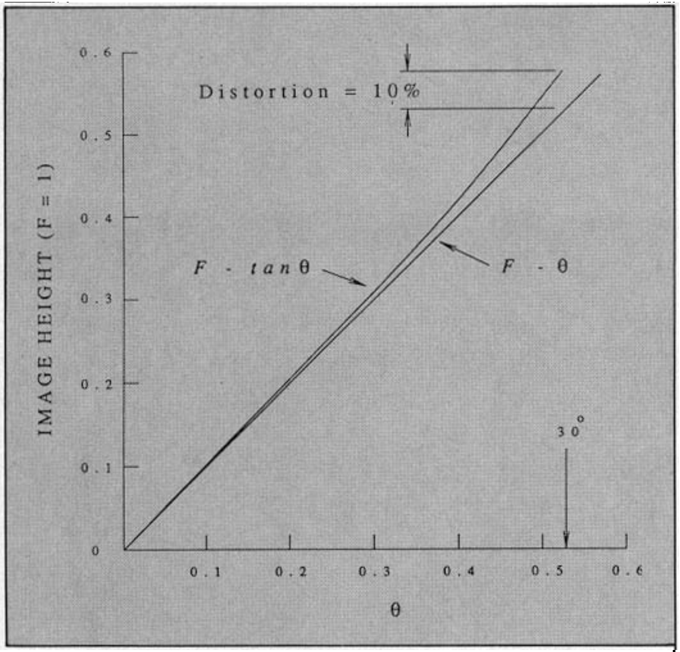


FIGURE 1. The difference between the F- θ image height conditions.

the scan line is proportional to the tangent of the scan angle. Figure 1 is a plot of the image height of a zero-distortion lens plotted against the scan angle θ. The curve departs from a straight line which is required for a constant velocity scan. As the angle increases, the zero-distortion lens images too far out on the scan. The spot moves too fast near the end of the scan line. The departures from linearity can be reduced by fitting a different straight line to the F-tan θ curve to redefine the focal length from the normal paraxial ray definition. The altered focal length is called the callibrated focal length.

When the field angle is as large as 30°, the residual departures are still not small enough. The departures from linearity can be further reduced by introducing third order undercorrected distortion (pincushion). Designing the lens to balance third and fifth order distortions further reduces the departures from linearity to the degree shown in Fig. 2. At a 30° field angle, the rate of change of spot position starts to near the edges of the scan. While the curve shown in Fig. 2. shows that the deviations from linearity are small, the rate of change is starting to get out of control. This will turn a letter "o" into an ellipse. A 30° scan is close to the limit that one can correct a scan lens and adequately meet the F-θ condition.

■ The telecentric condition

There are applications which call for telecentric scan lenses. In a telecentric lens, the central ray passing the entrance pupil emerges perpendicular to the scanning plane. This condition is required when reflected light from the scan line is to be reflected back through the system and is used to record positions on the scan line. Telecentricity also helps remove position errors when the scanning surface is not flat. Note that the last lens has to have a diameter greater than the scan line length, so this limits the size of the scan length to practical lens sizes (10 to 12 inches in diameter). The lens shown in Fig. 3 is a telecentric lens that covers a 16 mm. scan line.

■ Gaussian beam effects

Laser scanning systems usually operate with Gaussian beams. The intensity in a Gaussian beam decreases symmetrically from the center of the beam to the edge. Theoretically the intensity becomes zero at an infinite distance from the center of the beam. Normally the beam diameter is defined by the diameter where the beam intensity reaches the $\frac{1}{e^2}$ (I=13.5%) level. The beam from the laser is usually expanded, with an afocal telescope, to a larger diameter before it reaches the scanning element; the beam is truncated by the telescope lens apertures.

The ratio of the entering beam diameter to the design aperture of the lens determines the diameter of the final scanning spot. Figure 4 is a plot of a constant k versus the ratio of the beam diameter D_B over the lens design aperture diameter D_L.[2] The diagram shows the curves for k for the 13.5% and the 50% intensity levels of the image. The diameters of the image at the two intensity levels are given by the following equations:

$$d_{(\frac{1}{e^2})} = 1.83\lambda(F - number) \quad (1)$$

$$d(50\%) = 1.2\lambda(F - number) \quad (2)$$

There are several points to consider in the truncation of a Gaussian beam. The Airy disk formula for the spot diameter has 2.44 as the constant k, so it appears that the Gaussian beam image is smaller than the Airy disk. However, the Gaussian beam coefficient refers to the 13.5% intensity level in the image, while the Airy disk diameter refers to the first zero in intensity.

The shape of the intensity distributions for the two cases is shown in Fig. 5. These curves show that the Airy disk pattern is narrower than the truncated Gaussian beam all

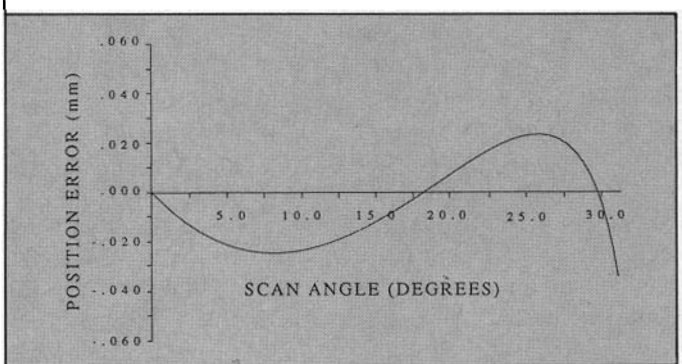


FIGURE 2. Third and fifth orders, and focal length, used to reduce F θ displacements.

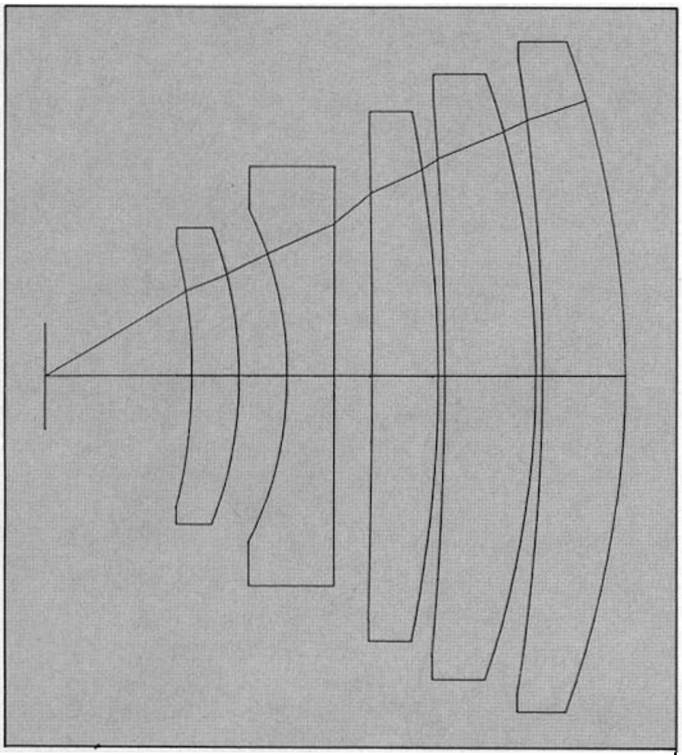


FIGURE 3. A wide angle scan lens: F = 100, f/24 FORMAT 52.4.

the way down to zero intensity. On the other hand, the Airy disk image does spread more energy out in the rings of the image than the Gaussian beam does.

The decision on how to truncate the beam depends on the applications. If the task is to record as many pixels as possible on a given scan line, then heavy truncation, to achieve an Airy disk, is the way to do it. This provides a sharp writing point, but the exposure level has to be carefully maintained to record the same size spot across the entire scan length. This in turn imposes a tight requirement on uniform velocity. Heavy truncation also reduces the total energy extracted from the laser beam so the laser power may have to be increased.

When the task is to put as much energy as possible into a given encircled area, then it is better to use less truncation. In this case, the exposure level is not as critical.

There is a good example of writing with the tip of the imaging point. It is being used in modern photolithography for printing micro-circuits on wafers. With optical lenses, it is possible to print smaller geometries than expected from the diameter of the Airy disk. This has been achieved by carefully controlling the uniformity across the exposed area and by not overexposing.

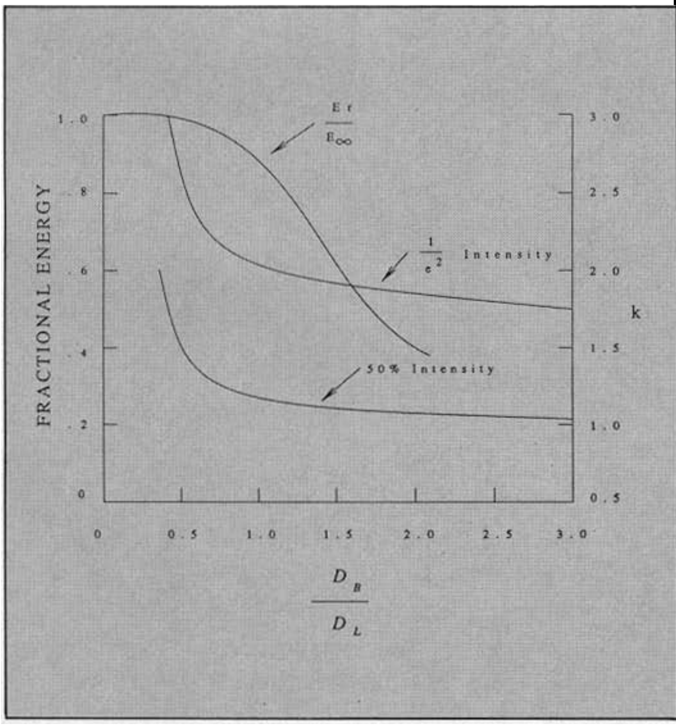
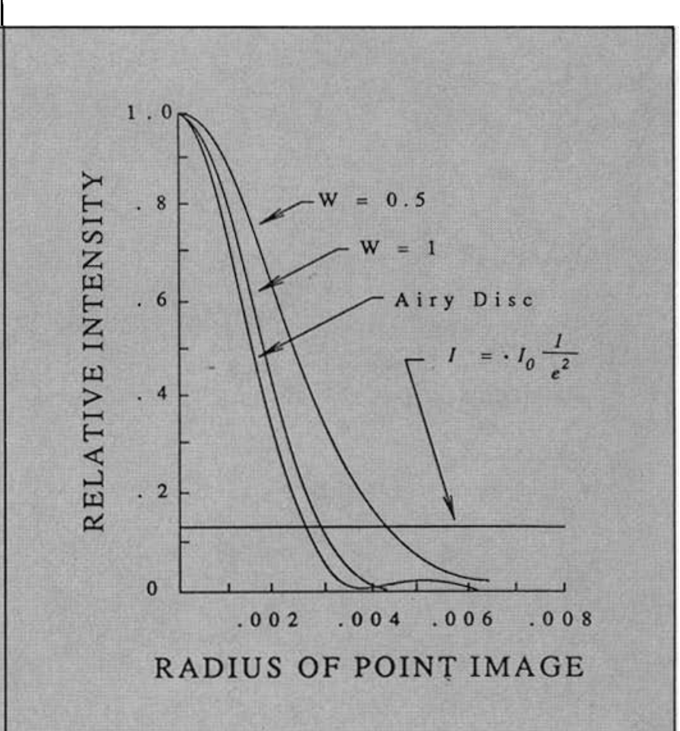


FIGURE 4. Variation of image spot diameter with truncation ratio $\frac{D_B}{D_L}$ and fractional energy passing through lens aperture.



FIGURES 5. Effect on spot diameter of truncating a perfect Gaussian beam. $W = \frac{D_B}{D_L}$.

Beam diameter, scan angle and length, number of pixels and addressability

The total number of pixels along a scan line is a measure of the optical achievement. The number of pixels is given by:

$$n = 2D_L\theta/k\lambda \qquad (3)$$

where $n = L/d$
d = spot diameter
L = length of scan
D_L = diameter of lens design aperture
θ = the half scan angle

Systems for generating half-tone dots usually specify the overlap of pixel elements. They can be overlapped by one half of the $\frac{1}{2}$ pixel diameter. This results in an MTF of approximately 50%. For the generation of line art the pixel elements can be overlapped to one quarter of the pixel diameter. This amount of overlap makes uniform black lines with adequate resolution even though the MTF is less that 50%. The pixel elements mentioned in the lenses to be described are defined by the diameter of the $\frac{1}{2}$ intensity level. There are usually two to four times as many addressable points.

When designing laser scanning systems, it is important to clearly understand the differences between pixel size and addressability. Addressability refers to the minimum separation between adjacent information spots to be written on a scan line.

Duty cycle

The "duty cycle" refers to the fraction of time the laser scanner is writing. A low duty cycle scanner writes for a small fraction of time—as a result, the scanning speed must be increased and the exposure time reduced. To compensate, a more powerful laser must be used.

There are two duty cycles to consider when using polygon or hologon scanners.

1. The mechanical duty cycle (MDC) is defined as:

$$MDC = 1 - D_B/A \qquad (4)$$

A is the dimension of a facet. The ideal MDC would be one, but this would require a beam diameter of zero.

2. The angular duty cycle (ADC) is the ratio of the beam scan angle to the angle subtend of the facets. This is given by the equation:

$$ADC = 2\theta N/360M \qquad (5)$$

where

N = number of facets
M = beam sweep angle/polygon rotation angle

Ideally, the ADC and the MDC should be equal and as close to 1 as possible.

M for a polygon or mirror is 2, while it is 1 for a holographic plane grating scanner.

To improve the angular duty cycle, Eq. 5 shows that θ and N should be large. A large θ helps keep the beam diameter and focal length small, but the large angle θ makes it difficult to achieve uniform velocity of scan. Increasing the number of facets also helps but requires an increased polygon diameter to provide an adequate MDC; this adds considerably to overall costs.

Note that an important advantage of holographic plane grating scanners is that M is 1, so the angular duty is better by a factor of 2 over the polygon. This factor is difficult to make up by increasing the number of facets or the scan angle of the lens.

Polygon scanners

Polygons are used extensively in scanners. The Cannon laser printer commonly seen in offices has now reached production of a million new units per year. These printers use a rotating polygon and cylindrical optics to correct for prism errors and produce about 300 dots per inch. As the number of pixel elements and the length of scan increases, the polygons are becoming more and more expensive.

Further, high resolution scanners nearly always involve small cross scan errors. Such errors are caused from pyramidal facet errors and wobble in the rotation axis. To reduce these errors to an acceptable level, some modern systems now require facet pyramidal precision in the range of one second. This is difficult when axis and facet errors are additive. Some of the lower quality scanners have been able to overcome this problem by using cylindrical elements.[3,4,5] These elements are not popular in high precision lenses because of both cost and sensitivity to alignment. Also they do not correct the wobble or pyramidal errors for the entire length of the scan.

The present trend is to use precision bearings and polygons machined on ultra precision machines, but such units are becoming large and expensive. And at some of the scanning speeds contemplated, the edges of the facets cause air turbulence, resulting in vibration and image distortion. However, the polygon does have an advantage—it is achromatic, while its competitor, the holographic scanner, is monochromatic.

Holographic scanners

The plane grating holographic scanner shows promise in meeting some of the most demanding scanning requirements. This type of scanner uses deep groove gratings made by interfering two plane waves incident upon a photo resist coating on an optical flat. The angle between the interfering beams is then adjusted to achieve fringes on the

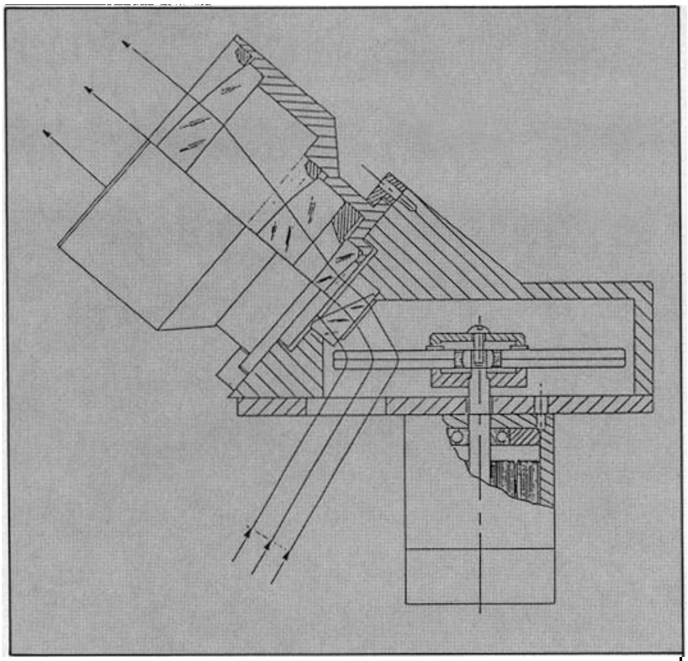


FIGURE 6. Holotek StraightScan lens.

order of one micrometer spacing. The developed grooves have an aspect ratio of nearly one. When used in transmission, they have a diffraction efficiencies over 90%. Their plane gratings are placed on an optical flat disk in the form of pie shaped wedges with grooves running perpendicular to the radius of the disk. Kramer[6] has shown that if the angles of incidence and diffraction are equal, the scan is insensitive to rotation wobble.

However, when this condition is met, the scan line develops a bow rather than the desired straight line. The bow can be straightened by passing the diffracted beam through a prism that inserts a corrective curvature. The two counteracting bows reduce the final bow to tolerable limits. Such a system has been designed and manufactured by Holotek Ltd. It is called the StraightScan™-2P scanner. A cross sectional view of the system is shown in Fig. 6.

A few examples of scan lenses

The lenses used in polygon and holographic scanners are similar, although the lenses used with the prism, for a holographic scanner, require a slightly different distortion correction to meet the F-θ condition.

The following designs are close to the boundaries of what can be expected of scanning lenses. Extensions beyond them will require considerably more complexity.

■ A reasonably wide angle scan lens

Figure 3 shows a five-element scan lens that covers a half scan angle of 30 deg. This lens can be used at a focal length of 100 mm. at *f*/23.8. At this focal length it can form 700 spots per inch, following the F-θ law to within 0.2% over the field. The lens uses the strong refractions on the fourth and fifth lens surfaces to achieve a careful balance of the distortion curve and excellent correction of the F-θ condition. The deviation curve has the same shape as the curve in Fig. 3. The air space between surfaces 2 and 3 is also an important control in the balance of third, fifth, and seventh order distortion. This air space has to be accurately positioned in the mounted lens.

This lens was evaluated from the U.S.P. 4,269,478 and was designed by Maedo-Yuko. The version chosen from the patent may not represent the optimum for this design, but it does provide a close example.

■ A high speed telecentric lens

The lens has a focal length of 48 mm and operates at *f*/3. It is telecentric and follows the F-θ law to 0.1%. It covers a 16 mm scan length with images less than 2 micrometers in diameter. This corresponds to 8,000 pixels per scan and 12,700 per inch. It was designed for a wavelength of 414 nanometers.

There is a story behind this lens. It was designed by the author, but it is not a nice lens to make because the last element is almost completely meniscus, making it difficult to center and mount. A valiant effort to eliminate the strong meniscus lens in the rear and replace it with a plano concave field flattener met with no success. Berlyn Brixner attempted to improve it with the Los Alamos program. He started the design and ran it several times, but it stayed in the same region and made no substantial improvement. He then suggested removing one of the central elements and giving it another try. This resulted in the lens form shown in Fig. 7. This design was a much better lens to make and had a slightly better correction. Apparently the optimization methods we use do not provide the information to suggest that an element should be eliminated. Perhaps the two nearly concentric lenses were a clue.

■ A telecentric, achromatic scan lens

The final example, Fig. 8, is a high quality scan lens requiring some color correction. This lens has a focal length of 51.5 mm and operates at *f*/2.0. It is used in a system that can deflect a spot to any position within a circle 20 mm in diameter. The image spot is 4 micrometers in diameter over the entire circle. The lens is complex because it has to provide for scanning in two different wavelengths which is difficult to do in lenses where the entrance

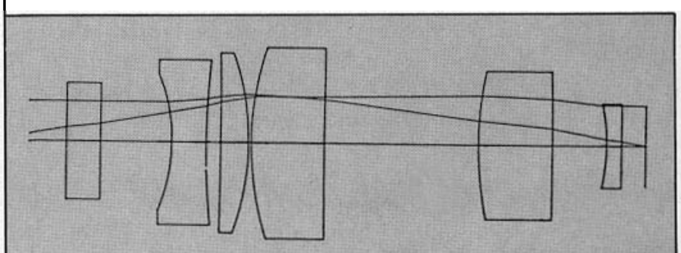


FIGURE 7. Brixner five-element lens: F = 48, f/3, FORMAT 8M.

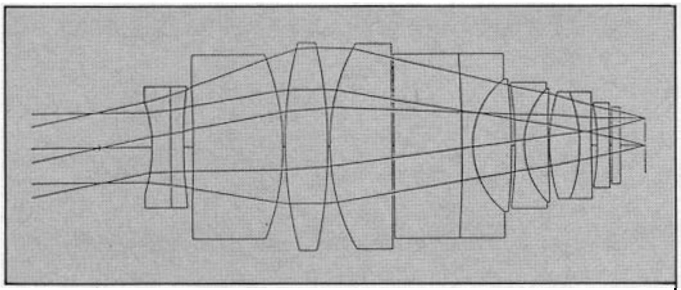


FIGURE 8. A telecentric, achromatic scan lens.

pupil is outside the lens. This lens was designed by David Stephenson of Melles Griot-OSD.

General considerations for laser scanner lenses

Up to now, scan lenses have been easy to design. But the last two designs shown are demanding on design, manufacturing, and assembly. The number of shops that can make therse lenses perform up to the design is limited. Still, the possibilities for spectacular performance are great in information transfer.

Skeptical scanning lens customers need only reflect on the parallel case of lenses for photolighography. Fifteen years ago, photolithographers considered a $10,000 price tag on a lens to be ridiculous; today, they are willing to pay several times that price. After seeking alternatives, they now appreciate the remarkable properties of precision lenses: they passively transfer hugh amounts of information at the speed of light and they do not wear out with use. Photolithographers have discovered that such lenses can perform their task beyond the predictions of simplified criterion. Scanning lenses hold similar promise.

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