Scanning Lenses and Systems

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Laser scanning systems using galvanometer mirrors or rotating polygons require special scanning lenses to create flat (planar) imaging fields. Although standard scanning lenses provide the flat field, the distance traveled by the scanned spot is not a linear function of the deflection angle. F-theta lenses provide a perfect solution by adding a specific amount of barrel distortion to the scanning lens and by eliminating the need for electronic correction. F-theta lenses are ideal for most marking, writing, and photoresist exposure applications, while telecentric F-theta lenses are suited for cutting and drilling applications.

Shortly after the invention of the carbon-dioxide laser in 1964, scientists and engineers began using the laser for a variety of cutting, welding, and drilling applications which not only required the workpiece to be positioned precisely at the focal point of the laser beam, but also for the workpiece to be moved, in an intricate pattern, with respect to the focal point. Thus laser scanning was born. The early scanning workstations were either fixed-beam systems, wherein the workpiece was placed on an x-y (or x-y-z) stage, or moving-beam systems, wherein the workpiece was fixed and the focal point of the beam was moved over the workpiece by series of mirrors and articulated robotic arms. In either case, the focusing optic was similar to a simple lens, used on axis, as shown in Figure 1. These scanning systems are still in use today for applications requiring large-scale motion (e.g., auto-body welding).

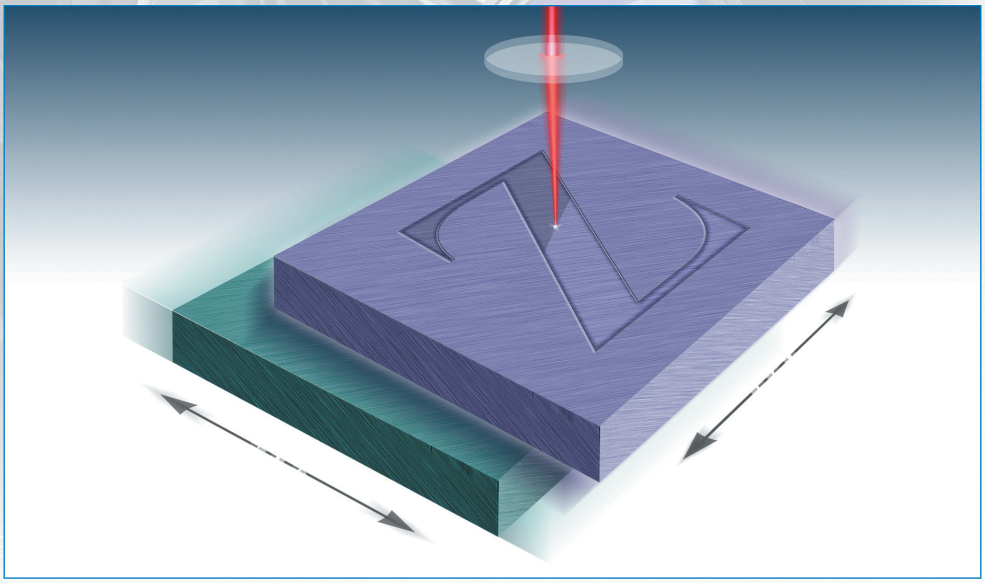


Figure 1: Fixed-beam laser cutting station

As newer lasers appeared and writing, pattern-making, and photoresist exposure applications (among many others) were developed, the need for faster, less-expensive, and more compact scanning systems became apparent. One of the earliest of these was the drum scanner, shown in Figure 2, which is used extensively in plate making for offset printers. Essentially a reconfiguration of a moving-beam system, the drum scanner uses a simple lens to focus the beam.

A rotating right-angle prism positioned after the focusing lens directs the beam onto an offset plate attached to the inside of the drum. During scanning, the lens/prism combination moves down the axis of the drum, line by line, until the plate is completely exposed. The drum scanner was a significant advance because it significantly reduced the size and weight and number of moving parts, the mechanical complexity, and the cost of the system. It was, however, limited in the size and type of materials that could be addressed.

The next evolution in laser scanning reduced the complexity of the system further by inserting a scanning mirror (or mirrors) behind the focusing lens. One version, used for single-axis scanning, uses a rotating polygon mirror as the scanning element. For area (x y) scanning, small mirrors are mounted on two high-speed galvanometers, one for each axis (see Figure 3). The small size and minimal inertia of the mirrors allow very rapid scanning. In both cases, the position of the lens is fixed, but it must focus the scanning beam onto a flat surface. Obviously, a simple lens is no longer adequate.

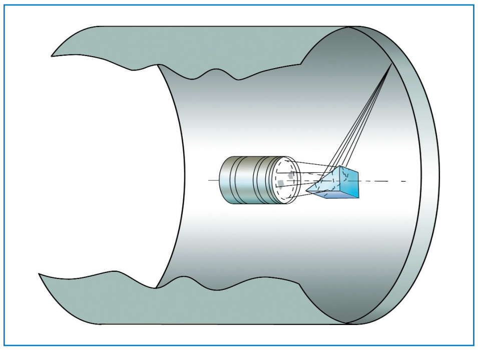


Figure 2: Drum scanner for offset-printing-plate making

Laser Scanning Requirements

There are five critical requirements for any laser scanning system:

1. the beam must be focused to a spot on the workpiece small enough that the energy density and/or resolution is sufficient to accomplish the task;
2. the spot size should not change significantly over the course of a scan;
3. the scan rate (and thus the dwell time at any given point on the workpiece) should be constant as a function of the input beam angle;
4. the angle of incidence of the beam on the workpiece should be appropriate for the task at hand; and
5. the optics must be appropriate for the laser wavelength being used.

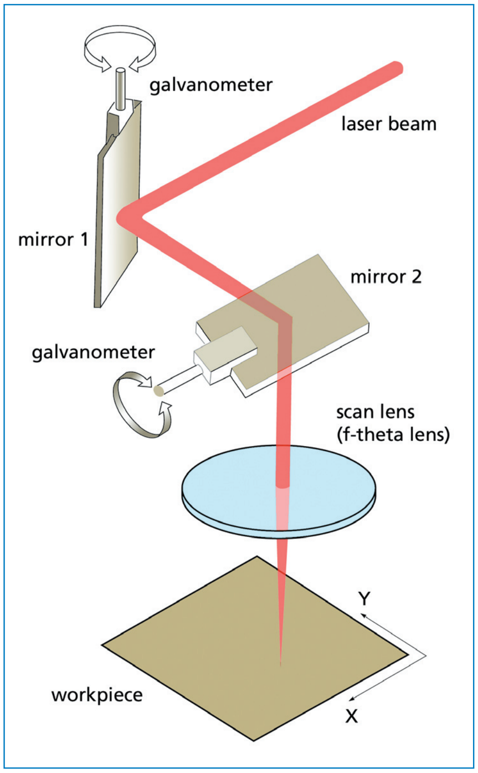
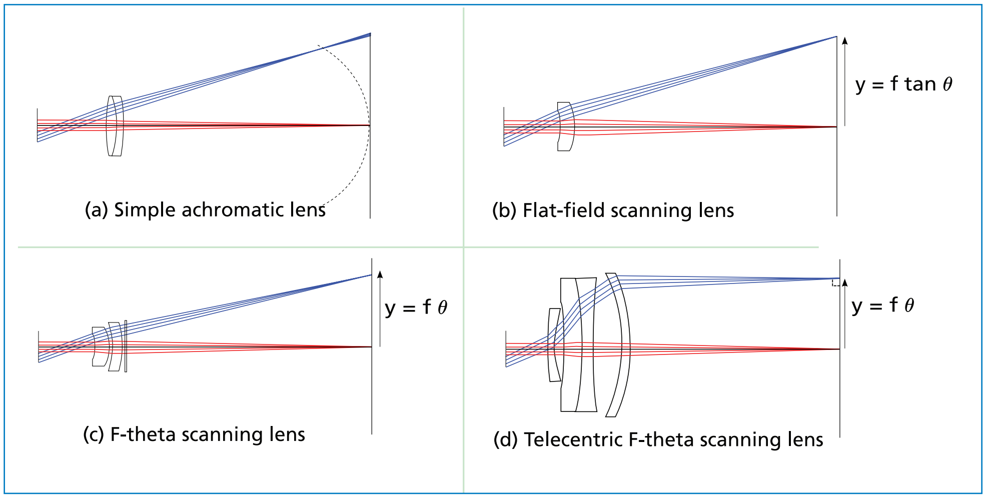


Figure 3: x-y galvanometer scanner



(a) Simple achromatic lens
(b) Flat-field scanning lens
(c) F-theta scanning lens
(d) Telecentric F-theta scanning lens

Figure 4: Comparison of lens performance

Figure 4 and Table 1 compare the performance of four types of lenses when used with a galvanometer scanning system. At zero deflection (the paraxial condition), all provide the same diffraction-limited focused spot. As the deflection increases, the performance varies widely.

Simple Lens

In this case, an optimized two-element achromatic lens is used as an example because it provides better off-axis performance than a single-element plano-convex lens. The focal plane of the lens moves away from the surface of the workpiece as the deflection increases, as shown by the dotted line in Figure 4a. Consequently, the spot area at the surface of the flat workpiece expands dramatically from a few tens of square microns to almost two-tenths of a square millimeter, with power densities dropping accordingly. Consequently, this type of lens can be used in a galvanometer scanning system for only very small scan angles (<2°).

Flat-Field Scanning Lens

This is usually a one- or two-element lens designed so that the focal plane of a deflected beam is always a flat surface, as shown in Figure 4b. For a theoretically perfect lens, the beam waist of the focal spot (i.e., the diameter of the beam at the focal point in the plane perpendicular to the beam) is independent of scan angle. However, because the beam is striking the workpiece at an angle, except at zero deflection, the spot on the workpiece is elongated by $1/\cos\phi$, where ϕ is the output scan angle (see Figure 5). Fortunately, in most cases, this is not an issue because the change in spot size and power density is typically less than 2 percent for a 10-degree deflection and only about 6 percent for a 20-degree deflection. The major issue with the standard scanning lens is that, in the absence of distortion, the distance y that the spot travels across the flat focal plane in a linear direction is given by

$$y = f\ \tan(\theta_y)$$

where f is the effective focal length of the lens and θ_y is the deflection angle of the beam. In other words, the scan velocity is not constant with

Scan Angle θ	Output Angle ϕ	Normalized Parameter			
		Spot Diameter		Spot Area	Power Density
		Major Axis	Minor Axis		
Simple Achromat (EFL = 160 mm)					
0°	0°	1.0	1.0	1.0	1.0
5°	4.9°	8.4	4.3	3.6×10	2.8×10^{-2}
10°	9.5°	30.8	14.2	4.4×10^{2}	2.3×10^{-3}
15°	14.0°	68.5	31.2	2.1×10^{3}	5.0×10^{-4}
20°	18.6°	126.0	56.7	7.2×10^{3}	1.0×10^{-4}
Basic Flat-Field Scanning Lens (EFL = 189 mm)					
0°	0°	1.000	1	1.000	1.0
5°	3.3°	1.004	1	1.004	0.9960
10°	6.5°	1.015	1	1.015	0.9852
15°	9.7°	1.035	1	1.035	0.9662
20°	12.7°	1.064	1	1.064	0.9398
F-Theta Lens Scanning Lens (EFL = 189 mm)					
0°	0°	1.000	1	1.000	1.0
5°	3.3°	1.004	1	1.004	0.9960
10°	6.5°	1.015	1	1.015	0.9852
15°	9.7°	1.035	1	1.035	0.9662
20°	12.7°	1.064	1	1.064	0.9398
Telecentric F-Theta Scanning Lens					
0°	0°	1	1	1	1
5°	0°	1	1	1	1
10°	0°	1	1	1	1
15°	0°	1	1	1	1
20°	0°	1	1	1	1

Table 1: Comparison of Scanning Lenses

respect to the scan angle, but it accelerates if θ increases at a constant rate, violating condition 3 in the list of critical scanning requirements.

Other parameters are needed to fully specify a scanning lens (see Figure 5):

Mirror 1 Position (a_1): The distance along the optical path from the housing to the first (farthest) scanning mirror.

Mirror 2 Position (a_2): The distance from the housing to the second (nearest) scanning mirror.

Front Working Distance (FWD): The distance from the lens housing to the entrance pupil. For optimum performance, this should be coincident with the point ½(a_1+a_2).

Output Scan Angle (ϕ): The angle between the image plane normal and the paraxial ray of the output beam. For a telecentric lens, this angle is always 0°.

Back Focal Length (BFL): The distance from the vertex of the outermost glass element (objective or cover glass) to the paraxial focal point.

Back Working Distance (BWD): The distance from the lens housing to the paraxial focal point.

In some scanning lens designs the principal planes are located outside the physical lens; in those cases the BFL and BWD will actually be longer than the EFL.

Damage Threshold: This parameter is critical for any laser marking, etching or cutting system, particularly for applications using CO_2, higher-power pulsed or Q-switched lasers like Nd:YAG.

Consequently, the scan electronics must be designed to compensate for this deficiency. This is especially problematic for rotating mirror (polygon) scanners because the rotation rate is necessarily fixed.

F-Theta Scanning Lens

This lens, shown in Figure 4c, is designed to correct the scan-rate deficiency found in the standard flat-field scanning lens. By adding additional elements and a precise amount of negative (barrel) distortion to the lens, the distance the spot travels across the flat focal plane becomes

$$y = f\,\theta_y$$

so that the spot travel distance is directly proportional to the scan angle (in radians), significantly simplifying the drive electronics, albeit at the cost of additional size and weight in the lens. In all other respects, it is similar to the standard flat-field scanning lens.

Telecentric F-Theta Scanning Lens

In scanning applications such as marking and photoresist exposure, the fact that the laser beam hits the workpiece at a slight angle is only marginally relevant. However, for drilling and cutting applications it can be a cause for concern because the holes may be drilled at an angle instead of normal to the surface, or the cuts may have a chamfer on one edge. For those applications, the telecentric F-theta lens, shown in Figure 4d, is the best solution. By adding several elements to the lens, the system can be optimized so that the chief ray will always be normal to the workpiece, regardless of scan angle. Telecentric lenses are always larger than an equivalent nontelecentric lens because the clear aperture of the objective lens must be at least as large as the active scan area of the workpiece to allow the chief ray of the ray bundle to impinge upon the scan area along the normal to that surface.

Field Curvature and Distortion

The numbers presented in Table 1 for the example scanning lenses assume a perfectly flat focal plane and zero distortion, which is not the case with real lenses. Although designs are carefully optimized to minimize field curvature and distortion, these errors are always present to some degree. Figure 6 shows the performance of a custom CVI Melles Griot F-Theta lens with an effective focal length (EFL) of 160 mm and a maximum deflection angle (θ) of 25 degrees. Placing the zero-curvature point at the midpoint of the scan range limits the field curvature to 0.2 mm. Residual distortion (after subtracting out the F-theta correction) increases with scan angle, but it is limited to 0.12 percent at its maximum point. Unlike the simple lens case, where the entrance pupil is located at a vertex of, or inside the lens, the entrance pupil for a scanning lens is well in front of the lens. For ideal performance, the point of rotation of the

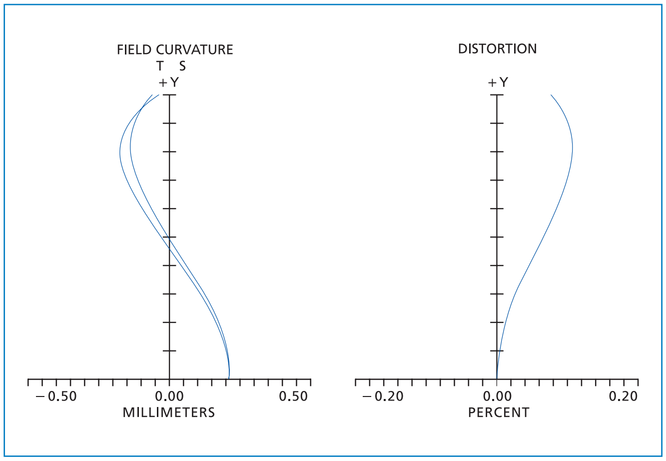


Figure 6: Field curvature and residual distortion for an F-theta lens (EFL = 160 mm, θ = 25°)

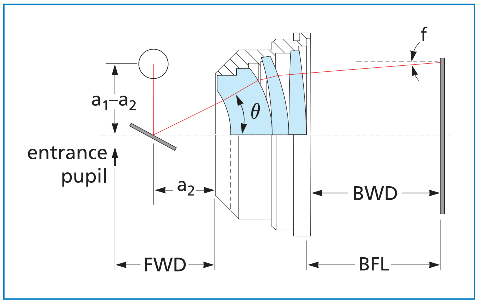


Figure 5: Scanning lens parameters

	-200 nm	-100 nm	-50 nm	λ_0	+50 nm	+100 nm	+200 nm
λ_0 = 1064 nm							
Change in Field Depth	-17.9%	-8.2%	-4.0%	0.0%	2.8%	15.1%	39.6%
Change in Spot Size	16.4%	5.2%	1.9%	0.0%	1.3%	2.6%	9.4%
Transmission Loss	4%	4%	4%	2%	8%	24%	36%
λ_0 = 633 nm							
Change in Field Depth	549.3%	158.8%	27.5%	0.0%	75.1%	156.8%	283.0%
Change in Spot Size	98.8%	23.5%	6.1%	0.0%	4.5%	13.2%	19.9%
Transmission Loss	4%	4%	4%	2%	3%	8%	24%

Table 2: Change in Performance of an F-Theta Lens as a Function of Wavelength

f-number	Maximum Scan Angle (θ)
≥ 50	36°
″ 30	32°
″ 20	25°
″ 12	20°
″ 6	15°
″ 2	10°

Table 3: Maximum Deflection Angle as a Function of Aperture

input beam should be located at the entrance pupil; otherwise, both F-theta performance and field curvature will be compromised. This is typically not an issue for single-axis scanners (one galvanometer), but it is a problem for two-axis scanners (two galvanometers) because the points of rotation for the two axes are not coincident. In this case, the mirror separation should be minimized, and the entrance pupil should be located halfway between the two galvanometer mirrors.

Selecting a Scanning Lens

When selecting an off-the-shelf F-theta scanning lens or specifying a custom lens, there are many parameters to consider (see sidebar, page 3), the most important of which are operating wavelength, focused spot size, scanning-field dimension, and the need for telecentricity. These factors place constraints on such parameters as entrance pupil diameter and location, as well as deflection angles and determine input beam diameter and galvanometer mirror locations and size.

Wavelength, Spot Size, and Focal Length

In a diffraction-limited scanning lens, the diameter of the focused spot, d, is given by

$$d = K \times \lambda \times \text{f-number}$$

where K is a constant related to input truncation and degree of pupil illumination, λ is the wavelength of the laser light, and the f-number is the EFL of the lens divided by the diameter of the entrance pupil. For a Gaussian laser beam, K=1.27, for a top-hat beam, K=2.44. (Note that, for a Gaussian beam, the entrance pupil should be 1.8 times the $1/e^2$ diameter of the beam, for a top-hat beam, the entrance pupil should be no larger than the beam itself.) Increasing the EFL increases the spot size. Increasing the entrance pupil (and the input beam diameter) decreases the spot size. Wavelength also determines the materials, overall design, and antireflection coatings used for the lenses. After a design is fixed, changing the input wavelength will have a significant negative impact upon performance. Table 2 shows the change in maximum field-curvature depth (normal distance between focal planes for different scan angles), spot diameter on the work surface, and reflection losses at the lens surfaces (for the paraxial ray) for two F-theta lenses, one optimized for 633 nm and the other for 1064 nm. Both have a maximum deflection angle of 25 degrees. The reflection losses assume four optical elements (eight surfaces) coated, in the case of the 633-nm lens, with a CVI Melles Griot HEBBAR /078 antireflection coating for visible wavelengths, and, in the case of the 1064-nm lens, with a HEBBAR /077 antireflection coating for near-infrared wavelengths.

Scan-Field Diameter, Deflection Angles, and Focal Length

In an F-theta lens, the planar field diameter L is given by

$$L = \text{EFL} \times 2\theta$$

where θ is the maximum deflection angle of the input beam. In general, it is most desirable to minimize the focal length by maximizing the deflection angle, consistent with the spot-size requirements.

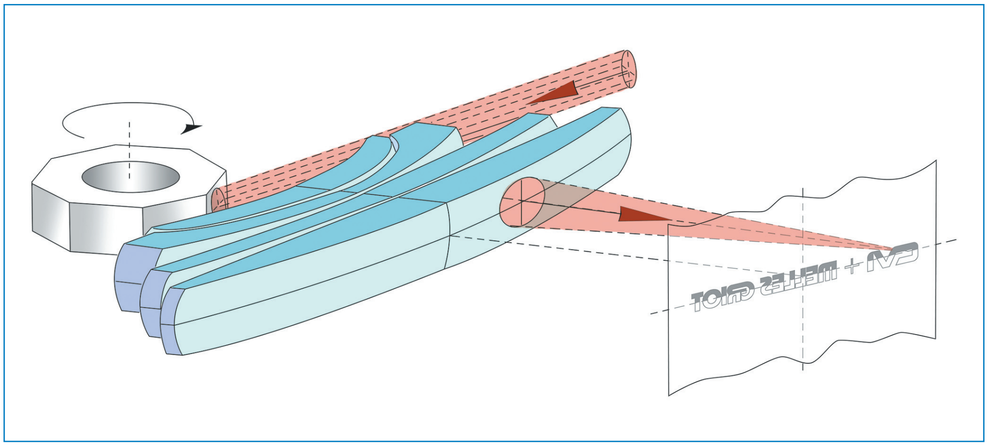


Figure 7: Single-axis polygon scanner with truncated F-theta lens

This has two significant advantages:

1. the size of lens apertures, mirrors, and optics can be reduced, resulting in a smaller package and savings in cost, and
2. the effects of angular nonuniformities caused by motor-bearing instabilities and facet-to-facet errors (with a polygon mirror) are reduced because aberrations scale with focal length. The practical limit on deflection angle is determined primarily by the f-number of the lens, as shown in Table 3. If the system will be scanning in only a single axis, a rectilinear lens system, such as that shown in Figure 7, should be considered. The cost is similar to that of a full-lens system, but the weight and size can be dramatically reduced.

Summary

Laser scanning systems using galvanometer mirrors or rotating polygons require special scanning lenses to create flat (planar) imaging fields. Standard scanning lenses provide the flat field, but the distance traveled by the scanned spot is not a linear function of the deflection angle, and, in most cases, complicated scanning algorithms must be used to overcome this deficiency. F-theta scanning lenses correct this problem by adding a specific amount of barrel distortion to the scanning lens and eliminating the need for electronic correction. F-theta lenses are ideal for most marking, writing, and photoresist exposure applications, but may cause angled holes and chamfers in cutting and drilling applications. Telecentric F-theta lenses should be used for these critical applications.

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