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Laser-Optical System of the IBM 3800 Printer

Abstract: A helium-neon laser, acousto-optical modulator and rotating polygonal mirror are used for the optical design of a computer printout system. This combination of technologies in the printer produces high-quality nonimpact printing at speeds of 23 000 to 52 000 characters per second. A new technique utilizing a cylindrical/toroidal lens pair is described which reduces, by two orders of magnitude, scan line displacement errors produced by the polygonal mirror. The optical design principles and alignment techniques used in the assembly are shown.

Introduction

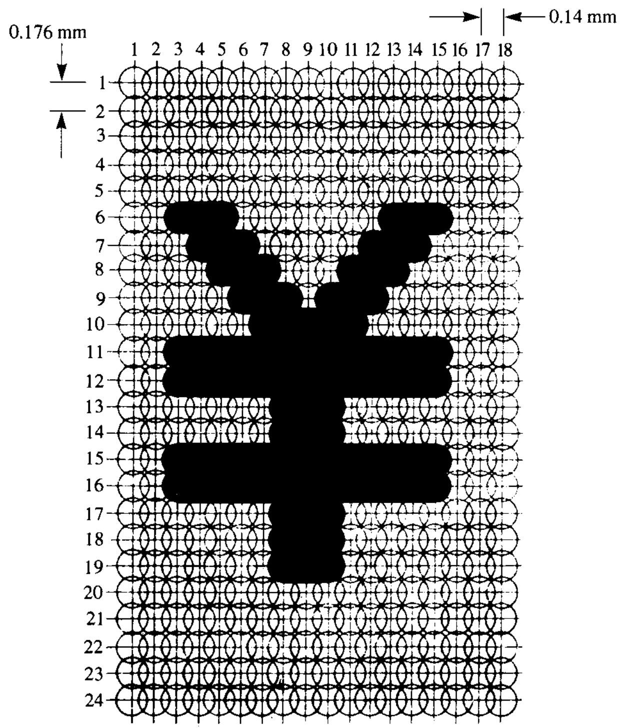
Laser scanning systems for optical displays, television displays and various forms of data recording have been under development in several laboratories since the late 1960s. Systems utilizing acousto-optic modulation and deflection of a laser source have been incorporated in television display systems [1, 2]. A highly accurate system for producing photomasks [3] and a data recording system for computer output microfilm [4] are other recent examples of laser scanning systems. Rotating mirror systems typically require very tight tolerances on facet-to-facet pitch angle errors. Pitch angle correction techniques using electro-optic analog deflections have been devised [5, 6], and an acousto-optic technique described [7]. Both of these correction techniques are difficult to implement on a production basis and/or their correction capacity is too small to significantly relax tolerance on the mirror facet-to-facet pitch angle. This communication [8] describes a laser scanning system for use in a digital nonimpact printer which incorporates a new technique for relaxation of those pitch angle tolerances.

Printing process

The IBM 3800 printer combines laser and electrophotographic techniques to produce high-speed computer printout. The printing process utilizes a light-sensitive photoconductive material wrapped around a rotating drum. This material is first charged and then exposed to light, which selectively discharges the photoconductor. Toner material is then distributed over the photoconductor. It adheres to the exposed areas, forming an image which is then transferred to continuous forms paper and finally fused to the paper with heat.

Two exposure techniques are employed. In one method, an optional full-page mask containing fixed information such as an accounting format may be placed close to the photoconductor surface and exposed once per page by a flash lamp. The second technique is to

Figure 1 An 18 × 24 matrix cell in which characters are formed by the laser beam. In the horizontal rows there are 457 cells per cm and in the vertical columns, 366 cells per cm.



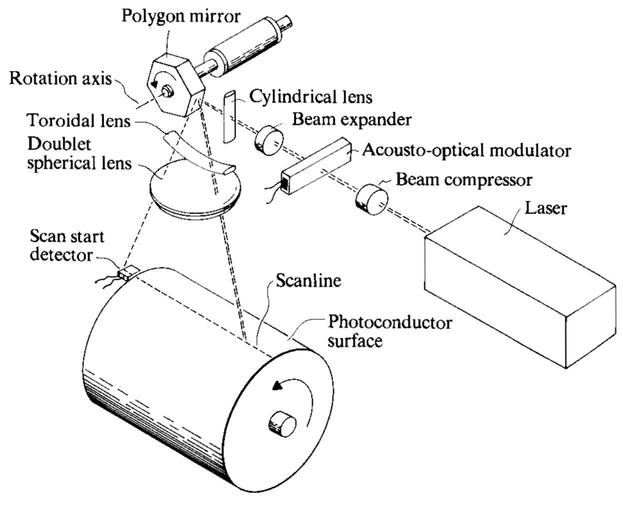


Figure 2 Laser subsystem, showing the polygonal mirror and scanning method.

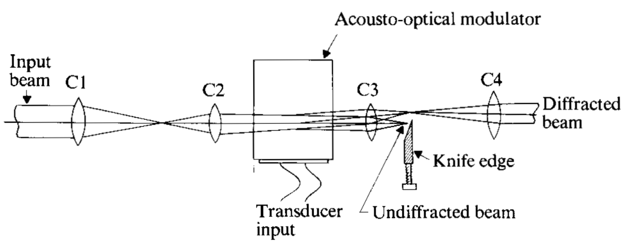


Figure 3 Detailed configuration of the compressor, modulator and beam expander. The beam is compressed by C1 and C2 and expanded by C3 and C4.

expose the photoconductor by using a focused laser beam which is scanned parallel to the drum axis with a rotating polygonal mirror. An acousto-optical modulator is employed to turn the beam on and off during the scan.

Characters are formed by the laser beam within an 18 × 24 matrix cell, as illustrated in Fig. 1. During the sweep of one facet, the continuously rotating photoconductor drum moves one vertical cell or 0.176 mm (366 cells per cm). The acousto-optical modulator can be turned on at any 0.14-mm space (457 cells per cm) in the horizontal direction. Characters nominally 0.4 mm in line width are formed with three image cells for vertical strokes and two cells for horizontal strokes.

Buffer storage and data arrangement are provided within the control unit. This allows the user to mix character size, font, and spacing. Depending on pitch and line spacing, the printer produces between 23 000 and 52 224 characters per second on an 11 × 14 7/8 inch computer page.

Laser subsystem overview

Figure 2 illustrates the laser subsystem. A helium-neon laser provides the energy for exposing the photoconductor mounted on the rotatable drum. An optical beam compressor reduces the laser beam diameter to minimize the rise time in the acousto-optical modulator. The beam expander that follows the modulator enlarges the beam diameter to the size required to produce the desired near-diffraction-limited focused spot size at the photoconductor. A knife edge placed at the second focal point of the first lens of the beam expander stops the zero-order beam from the modulator while allowing the first Bragg order to pass, essentially unattenuated. The cylindrical and toroidal lenses, which focus the beam in one azimuth on the mirror and then recollimate it, eliminate beam position errors at the photoconductor due to tilted mirror facets. The function of these elements will be described more fully later. The rotating mirror provides the necessary one-dimensional deflection and a doublet lens focuses the beam to a spot on the photoconductor.

The one-meter helium-neon laser operating in the TEM_{00} mode uses glass-sealed Brewster windows for long life. It is operated in a thermally controlled environment to produce constant laser power output over the printer operating temperature range of ±8°C. The laser, safety rated as class III, is contained fully within the printer, with exposure to the user prevented by safety interlocks. The printer is thus a class I product.

Figure 3 shows the beam compressor, modulator, and beam expander in greater detail. An acousto-optical glass modulator was selected, based on performance and commercial availability. The modulator, well documented in the literature [9], diffracts about 80 percent of the beam energy with low input electrical power. The laser beam polarization electric vector is aligned perpendicular to the direction of acoustic wave propagation to achieve maximum diffraction efficiency. The scanning laser beam is located at a new matrix position every 75 nanoseconds. The modulator rise time is determined by the beam diameter and by the acoustic wave velocity in the glass. To achieve reasonable rise times, a beam compressor is used to reduce the incoming laser beam diameter to approximately $\frac{1}{3}$ its original size.

The diffraction efficiency of the acousto-optical modulator as a function of the departure of the incident beam from the Bragg angle is given by [10]

$$I = I_0 \left[\frac{\sin\left(\frac{\pi \Delta\theta L}{n\Lambda}\right)}{\frac{\pi \Delta\theta L}{n\Lambda}} \right]^2 , \qquad (1)$$

where I is the intensity of the diffracted laser beam when the incident beam departs from the Bragg angle by $\Delta\theta$ in air, I_0 is the intensity of the diffracted beam with the incident beam at the Bragg angle, L is the diffraction cell interaction length, n is the refractive index of the cell, and Λ is the acoustical wavelength. With a cell interaction length of about 55 mm, an acoustical wavelength of about 0.1 mm and refractive index of 1.67, it can be seen that, to avoid any significant loss in efficiency in the modulator, the laser beam must be incident upon the acoustical waves within about 0.2 milliradian of the Bragg angle.

In order to ensure that the 0.2-milliradian tolerance can be met by essentially the entire laser beam, the wavefront distortion introduced by the first of the beam compressor elements may not exceed about $\lambda/5$ or about $\lambda/15$ for the second beam compressor lens. The wavefront distortion due to spherical aberration and defocusing (assuming a focal range of ± 0.5 mm) of plano-convex lenses of 60 and 15 mm is well within the $\lambda/5$ and $\lambda/15$ requirement. Initially the plano-convex lenses made for the beam compressor were found to be too sensitive to tilting or decentering (the optical axis of the element and the axis of the beam not collinear). Analysis of lens aberrations by Conrady G-sums indicates that the original crown glass elements of index of refraction of 1.52 produce a wavefront distortion exceeding the allowable limit if either element is tilted by 0.6 milliradian (two minutes) or more. Changing the glass to F2 (620364) provided a glass with an index of refraction not significantly different from the 1.618 required to reduce the G-sum (and therefore the coma) for the plano-convex lens to zero, thus increasing the tilt tolerance to at least 0.02 radian.

As indicated in the system schematic, Fig. 2, a polygonal mirror produces horizontal scans. The mirror facets are made several times longer than the horizontal extent of the beam at the mirror in order to reduce the fly-back time, i.e., the period during which the beam is partially on two facets and during which the reflected beams are outside of the field of the printing. Low fly-back time is essential to conserve laser power and modulator bandwidth.

Scan line displacement error correction

Figure 4 illustrates a scan line displacement error typical of rotating polygonal mirror scanners. In general, as each new facet is rotated into position, the facet normal is tilted a slight amount because of fabrication tolerances. The scan line deflected is given as

$$\Delta X = f \tan 2\Phi, \qquad (2)$$

where f is the final imaging lens focal length and Φ is the facet normal tilt from ideal. Typical applications of rotating mirrors usually require a pitch angle tolerance Φ of a few seconds. While mirror manufacturers can produce mirrors of this quality, yields and cost would make mirrors of this type impractical for use in the printer.

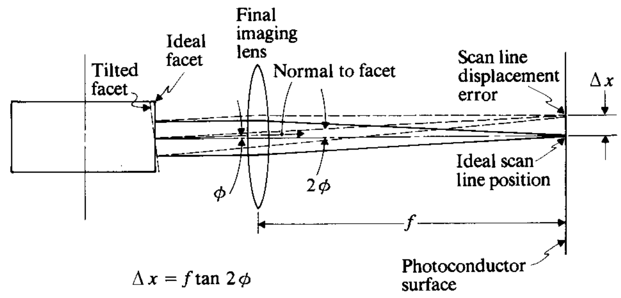


Figure 4 The scan line displacement error typical of rotating polygonal mirror scanners.

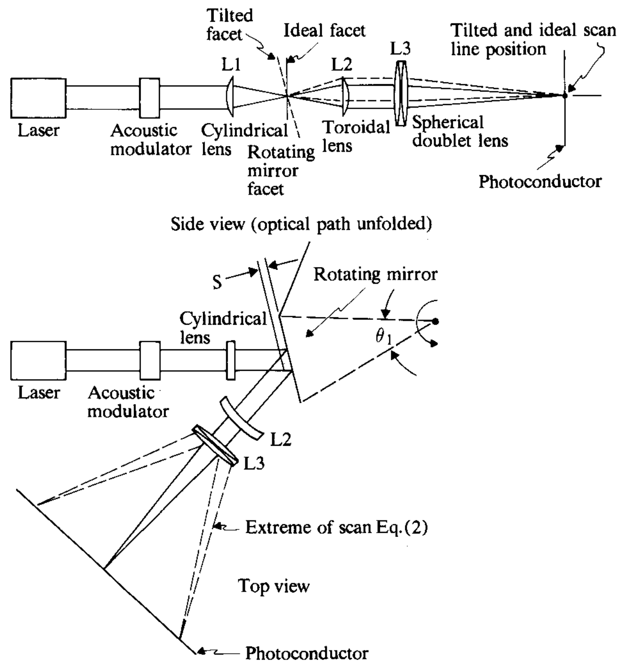


Figure 5 Cylindrical/toroidal lens correction technique.

In the printer we have added the two lenses illustrated in Fig. 5. Cylindrical lens L1 focuses the laser beam to a line image parallel to the scan plane on the mirror facet. The toroidal lens L2 then recollimates the laser beam and the spherical doublet focuses the beam to a circular spot on the photoconductor. Thus, combination of the toroidal lens and spherical lens images the mirror facet on the photoconductor in the plane normal to the scan plane. In the plane determined by the scanning beam, the beam remains essentially collimated in the rotating mirror space. Thus, if the mirror facets are tilted with respect to each other, the laser beam will follow slightly different paths to the photoconductor but the scan lines at the photoconductor will be superimposed.

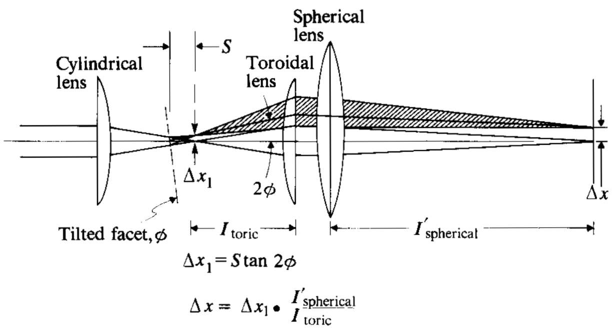


Figure 6 Scan line deflection due to sag S.

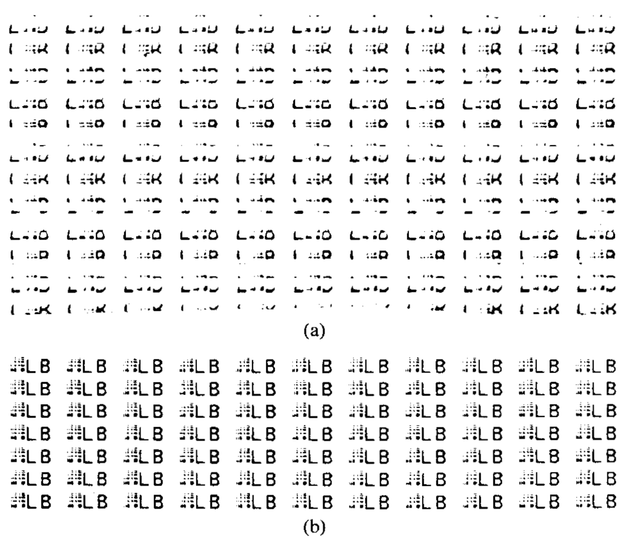


Figure 7 Print examples. (a) Without correcting optics. (b) With correcting optics.

The cylindrical/toroidal lens correction technique does not totally eliminate the scan line displacement error for all scan angles, because the line image formed by lens L1 does not remain focused on the polygonal mirror facet for all scan angles. The maximum defocus is approximately S, where S is the distance measured from the facet along the perpendicular to a circle scribed through all facet corners. Thus

$$S = r(1 - \cos\theta/2), \tag{3}$$

where θ is the facet central angle.

Defocus with rotational position of the mirror produces two main effects. The first is a deflection error and bowing of the scan line produced by a tilted facet, and the second is a decrease in the optical path length which, if uncorrected, would produce a defocused image at the photoconductor.

Figure 6 illustrates the deflection error. The mirror facet moves toward cylinder lens L1. For a tilted facet of pitch angle Φ the maximum scan line error at the photoconductor is given by

$$X = S(f_s/f_t)\ \tan 2\Phi, \tag{4}$$

where S is the maximum sag, Φ the facet normal error, f_s the focal length of the spherical lens, and f_t the focal length of the toroidal lens.

The facet normal tolerance increase G, where G = deflection without correction/deflection with correction, uses a cylindrical/toroidal lens combination. This is given by the expression

$$G = \frac{f_s \tan 2\Phi}{S(f_s/f_t)\ \tan 2\Phi} = \frac{f_t}{S}.$$

In the printer design, $G = 80$, allowing a significant facet normal tolerance relaxation. Figure 7 illustrates printing with and without correction. The printing in the upper portion produced without the correcting optics is severely scrambled due to misplaced scan lines.

The toroidal lens is illustrated in Fig. 8. The radii R1 and R2 were designed so that the optical path length from laser to photoconductor is very nearly constant for all scan angles, thus maintaining focus and constant spot size over the entire scan length. The lens radii R3 and R4 were designed to produce an on-axis focal length f_t equal to that of cylindrical lens L1. Alternatively stated, the design goal for the toroidal lens is to maintain the ray deviation α at a minimum for all scan angles. In the case of the printer, the maximum ray deviation is 30 microradians. Since glass toroidal lenses traditionally have been difficult to fabricate, the printer uses a molded plastic element which produces very little wavefront aberration.

Design of final spherical lens

The final spherical lens performs two optical functions in the laser printing system: 1) focusing the beam to the desired spot size over the scan length produced by the rotating polygon, and 2) providing negative distortion which will cause the focused spot to move at constant linear velocity.

The lens is a two-element design consisting of a front negative element and rear positive element. It is undercorrected for spherical aberration of the stop (which is located at the polygon surface) and is designed to provide exact spot location at 1.0 and 0.7 field. In the initial design stages a computer optimization program was used, the input beam was assumed to be collimated and no correcting optics were included. The final design and performance evaluation included the cylindrical/toroidal optics. Because the beam is focused on the polygon, actual positions of the polygon facet (which vary with scan angle) had to be included to ray trace the system accurately.

The apparent motion of the facet with scan angle precluded a completely automatic computer optimization, because the design tradeoffs had to be evaluated for discrete angular positions of the mirror. The final design produces a scanning spot which maintains a positional accuracy of ±0.013 cm over the 35.6-cm field. Ray trace data show that the largest horizontal and vertical geometrical spot sizes are 20 percent of the focused beam diffraction pattern diameter at the $1/e^2$ intensity points.

Alignment requirements and methods

Because the laser subsystem contains a multiplicity of optical elements in a three-dimensional configuration, optical components and mounts with dimensional tolerances small enough to obtain the required alignment in assembly without adjustments are not practicable. Adjustments for many of the optical components are therefore supplied. The lateral centering of the components is accomplished by using the subsystem laser and an *X-Y* position-sensitive light detector that can be mounted in a series of accurately located holes in the subsystem base casting. Focus adjustment is determined by the use of a small rotating slit scanner for measuring the laser beam diameter. Magnification, distortion and scan line displacement are measured by means of a fixture that holds a series of photodiode detectors in the scan plane.

Concluding remarks

We have described the optical design principles, optical components, and alignment requirements of the IBM 3800 nonimpact printer. This laser optical system employs a unique anamorphic correction system to greatly enlarge the normal facet-to-facet tolerances on the polygonal mirror. It also employs a He-Ne laser especially designed for long service life and an acousto-optical modulator. With a raster scanning approach and a minimum of optical elements, a computer output printer operating at speeds of 23 000 to 52 000 characters per second and producing characters of 18 × 24 matrix elements has been achieved.

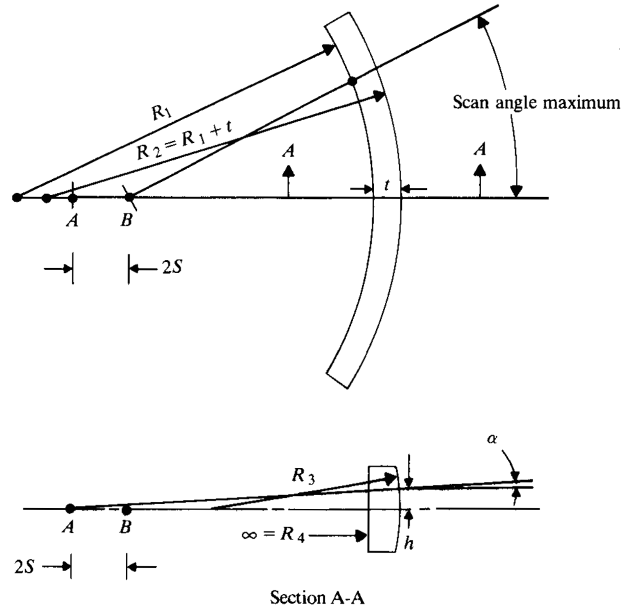


Figure 8 The toroidal lens designed for minimum ray deviation for all scan angles.

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