Laser Beam Shaping Applications

Fred M. Dickey, Todd E. Lizotte

Laser Beam Shaping in Array-Type Laser Printing Systems

Publication details

Andrew F. Kurtz, Daniel D. Haas, Nissim Pilossof
Published online on: 01 Mar 2017

How to cite: Andrew F. Kurtz, Daniel D. Haas, Nissim Pilossof. 01 Mar 2017, Laser Beam Shaping in Array-Type Laser Printing Systems from: Laser Beam Shaping Applications CRC Press
Accessed on: 11 Dec 2018

PLEASE SCROLL DOWN FOR DOCUMENT

Full terms and conditions of use: https://www.routledgehandbooks.com/legal-notices/terms

This Document PDF may be used for research, teaching and private study purposes. Any substantial or systematic reproductions, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The publisher shall not be liable for an loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.
3 Laser Beam Shaping in Array-Type Laser Printing Systems

Andrew F. Kurtz, Daniel D. Haas and Nissim Pilosof

CONTENTS

3.1 Introduction .................................................................................................... 58

3.2 Print-Head/Media Interaction........................................................................ 60

3.2.1 Laser Thermal Media ........................................................................... 61

3.2.2 Laser/Media Interaction—Depth of Focus ............................................. 63

3.2.3 Laser/Media Interaction—Multisource Print-Heads ......................... 64

3.2.4 Laser/Media Interaction—Spot Size, Shape, and Profile .................... 66

3.3 Laser Source Characteristics ........................................................................ 69

3.3.1 Laser Coherence and Beam Shape Issues ........................................... 70

3.3.2 Laser Arrays as Light Sources ............................................................... 72

3.3.3 Other Laser Sources ............................................................................ 75

3.4 Array and Cross-Array Optics ...................................................................... 76

3.4.1 Laser Smile Error ................................................................................... 77

3.4.2 Laser Smile Correction ......................................................................... 78

3.4.3 Operating Dependence of Laser Smile ............................................... 79

3.4.4 Optical Alignment Issues ...................................................................... 80

3.5 Direct Laser to Media Systems .................................................................... 81

3.5.1 Laser Emitters Mapped to the Media ................................................... 81

3.5.2 Multiple Discrete Lasers Mapped via Free-Space Optics ..................... 83

3.5.3 Array Printing with Discrete Laser Optical Systems ......................... 87

3.5.4 Fiber Array Print-Head .......................................................................... 89

3.5.5 Fiber Array Print-Head with Addressable Laser Arrays .................... 92

3.6 Modulated Subarray Laser Printing ............................................................... 93

3.6.1 Optical Configuration of a Monolithic Multichannel Print-Head .......... 93

3.7 Laser Array and Modulator Array Systems ................................................. 96

3.7.1 The Xerox TIR Modulator Array System ............................................. 97

3.7.2 Spatial Light Modulators ...................................................................... 99

3.7.3 An Array Print-Head with a Fly’s Eye Integrator ................................ 100

3.7.4 An Array Print-Head with an Integrating Bar Homogenizer ............... 104

3.7.5 Alternate Array Print-Head Designs ..................................................... 108

57
3.1 INTRODUCTION

In a variety of applications, including longitudinal solid-state laser pumping, fiber coupling for fiber lasers, and line printers, laser diode arrays have proven to be very effective light sources when combined with the appropriate beam shaping optics. As laser arrays can be designed in numerous ways, such as with phase-coupled single-mode emitters, uncoupled single-mode emitters, or uncoupled multimode emitters, the output properties of both the individual beams and the ensemble of beams vary dramatically. Inherently, many beam properties, including the output power level, beam profiles and beam propagation properties, beam coherence effects, and the overall device layout, are dependent upon the emitter structure. The optical systems that have been designed to work with these highly nontraditional light sources, which are anamorphic in both physical layout and beam properties, are themselves nontraditional, and typically employ a variety of modern micro-optical components. Within that context, a variety of unique systems have been developed for high-power, high-throughput printing applications, where the laser light is transformed into a linear arrangement of individually modulated beams and imaged onto a light-sensitive media. These systems typically combine the design and analysis techniques from classical imaging optics, illumination optics, and Gaussian beam optics into integral wholes. Certainly, many of the design concepts that have evolved to support the laser thermal printing application are applicable to other endeavors, of which laser projection is an example.

Traditionally, in a flying spot laser printer, the emitted laser light is shaped into a beam, swept through space by a deflector (polygon or galvo), and focused onto a media plane by an objective lens (often an F-theta lens). The focused light creates a written spot or pixel (the smallest image element), as input by some modulation means, to create the correct density of each spot, pixel by pixel. The modulation may be applied either directly to the laser via a control circuit or indirectly with an external device such as an acousto-optic modulator (AOM). As the laser spot is swept in the line scan (fast scan) direction to produce a line of image data, the media may be moved in the page scan (slow scan) direction to create a two-dimensional (2D) image.

Although flying spot printers can produce high-resolution images in high-throughput applications, when the trinity of requirements for high-throughput, high-resolution, and an insensitive media are encountered, other optical design approaches are required. Efficient printer designs typically use one or more high-power lasers, with the emitted light configured into a series of writing spots. These printers are configured like lathes, where the page scan (slow scan) motion is obtained by rotating a drum (at speeds up to 3000–4000 r/min), which holds the media, and line scan (fast scan) printing is achieved by translating a multitude (12–250) of writing beams in a direction parallel to the axis of rotation of the drum. For example, laser thermal
printers have been produced for the graphic arts markets, which simultaneously deliver high resolution (2400 dots/in; dpi) and high throughput (15 proofs/h) while printing on insensitive threshold-effect media (0.2–0.5 J/cm²). Typically, thermal media works by a dye sublimation or ablation process to create an impression when heat (light) is applied locally. Other exposure mechanisms that are employed by laser thermal media include polymer cross-linking and polymer phase changing within a coated layer. All of these media can provide image resolution as high as 3000 dpi, which is finer than high-quality AgX (silver halide) photographic media.

Multiple channel print-heads are rarely used in flying spot printers because of the complexity of the optical system. More typically, a print-head is moved in a swath-like manner over a rotating drum such that the entire media can be printed on. The media may be held on a flat bed, in an internal drum or external drum. The internal drum printer holds the image-recording media stationary, while the beam is deflected through the large field of a rapidly rotating monocentric optical system. By comparison, in an external drum printer, rotation of the drum carrying the image-recording media provides fast scan operation in one direction, while the print-head moves perpendicularly along the slow scan direction. The laser light propagates along the z direction, perpendicular to both the fast scan and the slow scan directions.

A multichannel print-head for a swath-type printer can be constructed in a variety of ways. For example, the print-head can employ a multitude of laser sources, each coupled into an associated optical fiber, with these fibers arranged linearly across the length of the drum, with each channel responsible for printing a portion of the media. Alternatively, an integrated print-head can be provided, wherein a multitude of laser sources is individually coupled into optical fibers, and the fibers are brought together into a small print-head to form a linear array of sources. Rather than creating an array of writing spots with a series of fiber-coupled lasers, a monolithic laser array can be used as the light source, with the linear arrangement of emitters imaged directly onto the media. In this case, each of the lasing elements must be individually addressable to provide the desired modulation to obtain the various pixel densities. Such systems possess both a lower unit cost and higher light efficiency, as compared with the systems that couple numerous lasers to optical fibers. However, when the individual laser emitters are imaged directly at the media, the printers are susceptible to the failure of even one element in the array, because a pattern error results. Furthermore, these printers are also sensitive to image artifacts caused by thermal and electrical crosstalk within the diode laser array package.

Alternately, the monolithic diode array source can be constructed with each lasing element split into an array of subarray laser sources. Light from each of the lasing elements of a given subarray is combined into beams (one beam per subarray), and the beams are directed onto the media. Each of the subarrays is directly and individually modulated to provide the image data input. While this approach reduces the sensitivity to thermal crosstalk and desensitizes the printer to the failure of lasing elements within a subarray, the optical design is both complicated and constrained to a limited number of channels by the laser structure.

More commonly, printing systems have been designed wherein a laser or laser diode array is used only as a continuous wave (CW)-driven light source with the
light incident on a spatial light modulator array, either as individual beams\textsuperscript{19,20} or as flood illumination.\textsuperscript{9,11,21} The pixels of the modulator array are imaged onto the media as an array of printing spots. The laser source is greatly simplified as it operates at full power without direct modulation. In addition, these printing systems, in which the modulator array is flood-illuminated by light from a laser array, are desensitized to laser emitter failure. In such systems, each emitter is imaged at high magnification to illuminate the entire length of the modulator array. However, as the array direction light emission profiles provided by typical laser diodes have both macro- and micrononuniformities, the resulting illumination can be significantly nonuniform. Without correction or compensation, this illumination nonuniformity at the modulator plane will translate into a variable pixel density with fields on the printed image, usually resulting in an objectionable level of image artifact. Thus, it can become necessary to incorporate uniformizing optics, such as a mirror assembly,\textsuperscript{9} a fly’s eye integrator,\textsuperscript{11} or a light pipe\textsuperscript{21} within the system design, such that the spatial light modulator array is properly illuminated.

Computer-to-plate (CTP) laser thermal printers, platesetters, or newsetters, are presently offered by a variety of companies, including Eastman Kodak Company (Rochester, NY), Presstek LLC (Hudson, NH), and Agfa Graphics NV (Belgium), as well as Dainippon Screen Manufacturing Co. Ltd (Kyoto, JP) and Hangzhou CRON Machinery & Electronics Co., Ltd (China). CREO Inc. (Burnaby, BC, CA) acquired Scitex Graphics (Israel) in 2000, and CREO was in turn acquired by Eastman Kodak in 2005.

### 3.2 PRINT-HEAD/MEDIA INTERACTION

As noted previously, the laser can interact with a medium to form an image in a variety of ways: (1) dye transfer or sublimation from a donor sheet, (2) ablation of dye from a support, (3) polymer cross-linking, and (4) phase change. Laser thermal printing can be used to produce directly viewable images on paper or transparencies. The principal use of laser thermal printing is the production of intermediates in the preparation of viewed images printed by a high-speed press with multicolor inks. Some of these intermediates are: (1) the laser thermal proof for the buyer of the press run to approve the image content and colors, (2) contact films for exposing photoresist-coated conventional printing plates, and (3) directly laser-written printing plates. In such cases, the print quality is dependent upon not only the quality of the laser thermal process but also the surface properties of the exposed and unexposed areas on the laser-written printing plate, ink properties, and \textit{dot gain} of the ink from the laser-written spot.

A laser thermal-written image can be generated in a variety of ways according to the properties of the thermal media and the printer, as well as the application requirements. For example, laser thermal printers have been designed for both continuous-tone, referred to as \textit{contone}, and half-tone printing. Continuous-tone laser thermal transfer printing, which has been previously discussed in considerable detail,\textsuperscript{22} is summarized here to provide a better understanding of head–media interactions.
3.2.1 Laser Thermal Media

One exemplary type of a laser thermal medium is the donor media. The laser thermal donor suited for continuous-tone applications is capable of transferring intermediate amounts of its coating of visible dye to a receiver when stimulated by the incident laser radiation. In particular, low-molecular-weight dyes are vaporized from the donor and transferred to a receiver when a donor is heated to temperatures higher than the dye’s vaporization temperature. This process is initiated by absorption of the incident focused light which then induces a large, rapid temperature rise within a small volume of the donor. Controlling the beam irradiance of the laser during raster scanning across the donor can produce well-defined images. No further chemical processing is needed, and all material handling can be performed in room light.

Figure 3.1 depicts a vertical section of a layer of infrared (IR) and visible dyes coated in a binder on the bottom surface of a donor sheet. Matte beads hold the donor at a fixed gap from the receiver and minimize sticking of the heat-softened dye layer to the receiver’s surface. The sequence of panels illustrates a laser, scanning from left to right, at four successive times. The dye layer is cool when the laser is first activated in the left panel. Accumulation of the laser energy heats the dye in the second panel, with fastest heating occurring at the beam’s focus, where laser irradiance is greatest. Dye nearest the laser captures more heat than dye farther along the beam’s propagation path as a result of the dye’s attenuation of the light. Heat builds up at the donor’s lower surface in the third panel.
because insignificant thermal conductivity or convection at the donor–receiver gap causes the donor’s lower surface to act as a thermal insulator. If dye at its vaporization temperature acquires its heat of vaporization, then this additional energy transforms the hot molten dye into free gas molecules, or possibly into an aerosol, which can condense onto the cooler surfaces of the receiver and surrounding donor. The fourth panel shows that as dye molecules transferred from the surface are removed, greater depths of the dye layer are uncovered with continued laser irradiance. Thicker deposits of dye can thus be formed on the receiver, providing the potential for modulated image density. Dye condensing on the receiver imparts some of its heat to that surface, warming parts of the receiver. Material in the laser’s heat trail on the donor cools back to ambient temperature by diffusion of heat to the surrounding unexposed donor.

The thermal profile within the dye layer can be analytically modeled as a static approximation and, more completely, as a dynamic phenomenon. In the absence of thermal diffusion, a scanning source generates a uniform temperature profile throughout the dye layer, which can be calculated by simply accounting for energy deposition. Multiplying the resulting static temperature by a proportionality factor representing the fraction of heat escaping by thermal diffusion provides an approximation for the temperature in the presence of thermal diffusion. The absorbed light energy elevates the temperature of the donor material above the ambient temperature in proportion to the amount and heat capacity per unit volume of material capturing that exposure. As part of the static temperature analysis, a uniform temperature approximation can be made, even though the Beer–Lambert law indicates that more heat is deposited on the side through which the light enters than on the side through which the light departs. The uniform temperature approximation is relevant for light incident through the support because, at the outer surface of the dye layer, a mild vacuum is provided, which has an extremely small thermal conductivity compared with the donor materials. This outer surface acts as a thermal insulator, causing heat to build up in the nearby material. This buildup of heat at the outer surface occurs when the beam scans slowly enough so that the time for the beam’s center to traverse the beam’s full width at half maximum (FWHM) is longer than the characteristic time for heat to diffuse through the thickness of the dye layer. By implication, the dye layer is thermally thin. Heat diffuses into the cooler plastic support and away from its location of most intense deposition at its entrance into the dye layer, further leveling the temperature profile across the thickness of the heated dye layer.

The typical laser thermal dye transfer medium is a threshold medium, meaning that the dye is transferred only from regions that retain enough energy from the absorbed laser light to convert the visible dye to its vapor phase. The exposure in excess of threshold constitutes the energy available for transferring the dye molecules from the surface of the donor. In general, less exposure is required by a thinner dye layer than by a thicker dye layer to attain the same image density, because the thin donor contains less material to be heated in its dye layer. Only a small fraction (~3%) of the energy beyond that needed to heat the visible dye to its vaporization point seems to be devoted to transferring the visible dye from the donor to the receiver. The rest of that energy presumably vaporizes volatile molecules, further heats nonvolatiles, decomposes some constituents, and mechanically deforms the donor.
The laser thermal dye transfer process can be considered to obey additive density in the slow scan direction so that the density profiles transferred by successive scan lines add if the donor is permitted to cool substantially to ambient temperature between fast scans.\textsuperscript{23,24} This basic property of the laser thermal imaging is a significant departure from the additive exposure mechanism of silver halide imaging,\textsuperscript{25,26} in which the exposure uniquely determines the image density, regardless of the time sequence for depositing that exposure onto photosensitive materials.

The hottest location in the donor inevitably trails the instantaneous beam center because the location in the donor at the beam center has only received light from the leading half of the beam. The trailing half of the beam subsequently attempts to make that location twice as hot. However, some of the heat deposited by the leading half of the beam has diffused away, reducing the maximum temperature attained. At slow-to-moderate scanning speeds, the hottest temperature occurs at the exposed outer interface of the dye layer as a result of the insulating character of that interface, and in spite of the initial deposition of more heat at the internal interface of the dye layer where it contacts the cooler support.

It should be noted that there are types of laser thermal media other than dye transfer media. In particular, many laser thermal media are fabricated using pigment layers. Laser thermal media can also operate by an eruptive process, in which an internal laser-heated layer expands abruptly through the over-layers on a localized basis.

### 3.2.2 Laser/Media Interaction—Depth of Focus

The necessity of heating the visible dye to high temperature in order to induce transfer requires that the laser beam be tightly focused. Broadening of the beam, caused by movement of the dye layer away from the plane of best focus, reduces the transferred image density. A depth of focus criterion can be determined by recognizing that the plane of best focus as the location that produces highest uniform density, and not necessarily the plane that exhibits the narrowest waist. In effect, the depth of focus becomes the distance from best focus that causes the image density to drop a specific amount,\textsuperscript{27} instead of using the more conventional size of the aerial irradiance distribution\textsuperscript{28} (e.g., the Rayleigh range). A representative curve of density versus distance from best focus is shown in Figure 3.2, which indicates that to hold a density variation on the receiver to less than 0.1 D requires the dye layer of the donor to be maintained within a 50 \(\mu\)m range about the plane of best focus throughout the image. This demand justifies the use of a mechanically precise apparatus for translating donors of consistent thickness in laser thermal printers, producing images with continuously adjustable laser thermal transferred density.

The use of larger printing spots hides spot placement errors and increases throughput in thermal media. However, the use of larger printing spots also lowers the system modulation transfer function (MTF) and makes it more difficult to balance or adjust the swath response to hide the intensity and placement errors, because interactions are extended across several neighboring writing spots instead of only to the nearest-neighbor spots. Nearest-neighbor interactions, which increase the output density provided by writing adjacent channels, occur when the optical writing spot is larger than the
scan line spacing. Alternatively, it can be stated that the energy from a single laser is used less efficiently than the energy from two or more laser spots that operate in proximity in both space and time when the optical writing spot is more than one raster line wide. The increase in efficiency is significant in determining the overall throughput of the system. The price for this efficiency is the increase in the nearest-neighbor interaction among the channels and a decrease in contrast modulation around the rim of a half-tone dot on a print. Furthermore, use of the nearest-neighbor effect also requires the use of channel compensation and calibration methods with a high fill factor, multispot print-head in order to strike a compromise among the densities exhibited by single, pair, and triple line patterns and an entire swath. Thus, the definition of the printing spot size is problematic, as the use of small writing spots increases MTF and makes nearest-neighbor effects more controllable but also reduces the effective depth of focus.

3.2.3 Laser/Media Interaction—Multisource Print-Heads

While there are viable laser thermal printing systems in which multiple laser sources work in parallel but in isolation, there are also many systems where the multiple laser sources are in sufficient proximity to incur laser source crosstalk or laser thermal media crosstalk (the nearest-neighbor effect) or both. Thermal interactions can occur between the temperature profiles produced in the donor by simultaneous exposure with multiple sources. These interactions are separate from thermally mediated influence of one source upon another source’s emission, which might occur if multiple sources are mounted upon the same substrate or heat exchanger. In laser thermal printing, the thermal interactions of adjacent writing spots on the donor typically combine in a favorable way, effectively using energy that would be squandered by writing with a single spot. In particular, writing with multiple adjacent spots
simultaneously enables some spots to exploit the skirts of their neighboring spots’ exposure distributions.

There are several design architectures for multiwriting spot print-heads.\textsuperscript{13,14} These can be grouped as those that have a line of adjacent writing spots or pixels spaced apart with a low fill factor or duty cycle (70\% or less), and as those that have the adjacent writing spots immediately (or almost) adjacent for a high fill factor, respectively. However, a significant efficiency advantage can be attributed to the high fill factor, multisource laser thermal print-head over the low fill factor configurations. The heating of a strip of media by a neighbor is the predominant advantage exploited by the multiple sources so that the nearest-neighbor interaction requires only ~60\%–80\% of the exposure required by a series of single beam exposures to generate the same rise in dye layer temperature.

In some systems, a low fill factor print-head can be made to simulate a high fill factor print-head by tilting the print-head relative to the medium.\textsuperscript{31–35} The tilting of a print-head relative to the medium is also an effective way to increase the printing resolution without having to fabricate the print-head addressing and pixel structures on a finer pitch. Figure 3.3 depicts a tilted print-head, showing that a high optical fill factor is provided by reducing the pixel pitch from the printing spot pitch (d) to the tilted printing spot pitch (Y). However, tilting the print-head introduces time delays between leading and lagging writing spots. Furthermore, the favorable nearest-neighbor thermal crosstalk effects at the media are somewhat reduced with a tilted print-head because some of that energy deposited by a leading spot escapes before

\textbf{FIGURE 3.3} Print-head tilted to reduce spot pitch (Y), while maintaining a constant Gaussian beam radius.
the successive lagging spot source exposes an adjacent location. Nonetheless, a tilted low fill factor print-head can still provide considerable benefit even when accounting for the difference between leading and lagging thermal distributions. Thermal time dissipation conditions can occur where a significant portion of a preceding neighboring spot’s heat from its exposure skirt remains available in the medium when the hottest part of the adjacent lagging beam arrives. Conversely, the second-neighbor interaction is predicted to be insignificant, as very little energy extends from one laser spot to another, two raster lines away.

In the case of the tilted print-head, lagging beams provide little benefit to the leading beams. In particular, the lagging spots are assumed to not contribute to dye transferred by the leading spots, relative to the experimental conditions of beam size, spacing, and thermal diffusion, because the thermal conditions present for a leading spot are unchanged by activating or deactivating the trailing beams. Because the leading laser in the swath of the tilted print-head of Figure 3.3 does not have the advantage of a thermal tail from any other beam, the leading laser transfers less dye if operated at the same power as the other lasers in the print-head, causing the artifact of a light line in the image. This swath edge artifact can be avoided by operating this leading laser as a dummy laser\textsuperscript{33,35} at a power just below the threshold for transferring dye on its own. The second laser in the print-head enjoys nearly the same advantage of preheating by this preceding dummy beam as each subsequent beam does from its first-leading neighbor.

Alternately, interleaving or interlacing\textsuperscript{32,36–38} enables the use of a low fill factor print-head with its writing spots spaced farther apart than the desired scan line spacing while avoiding the need to tilt the print-head. Interleaving can reduce interactions of nearest neighbors\textsuperscript{25} while maintaining constant print-head scanning speed or step size in the slow scan direction. On subsequent passes, scan lines are written in the gaps between scan lines from previous swaths.

The principal disadvantages of interleaving are as follows: (1) scan lines are not written in their ordinal sequence, (2) part of the leading edge and trailing edge of the scanned area are never filled in, requiring extra scans to complete an image, and (3) production of a desired density requires as much area-averaged exposure as single-source printing because the nearest-neighbor interaction is insignificant as a result of the greater spacing of scan lines exposed during a single swath. This last point of insignificant nearest-neighbor interaction can be an advantage for interleaving because nearest-neighbor artifacts can be avoided,\textsuperscript{39} such as difficulty balancing a print-head or accentuation of temperature profile shifts by varying scan line spacing. However, as interleaving lacks the nearest-neighbor interaction, no lasers are sacrificed as dummy lasers.

### 3.2.4 Laser/Media Interaction—Spot Size, Shape, and Profile

As many of the graphics applications require high-resolution printing in the 2400–3000 dpi range, the writing spot (or pixel) may need to be as small as 2.5–10 µm in size, although other applications have required less resolution (25–50 µm spots). In the array direction, the first-order writing spot size can be derived from the system
dpi specification, although other factors, including the light profile, nearest-neighbor effects, and media effects (e.g., dot gain with inks) may alter the optical specification. In the cross-array (fast scan) direction, the motion of the drum and media relative to the writing spot and the resulting smear (convolution) of the light and heat across the media may motivate a cross-array printing spot specification that is different (narrower) than the array direction spot specification. In practice, the writing spots of laser light incident to the media are often round or square in cross section.

The image quality of the printed pixels can also be dependent upon the light profile within the writing spots. Many laser thermal printing systems have configurations in which at least one axis (typically the fast scan, which corresponds to cross-array or cross-emitter) presents a nominally Gaussian profile focused spot onto the media. In the orthogonal (slow scan or array) axis, the light profile presented to the media may also be nominally Gaussian. However, there are several systems, such as those that flood-illuminate the entire length of a modulator array, which present a nominally uniform light profile, at least on a per-pixel basis. In the exemplary instance that the writing spot is Gaussian in the fast scan direction and uniform in the slow scan direction, the motion of the Gaussian beam across the media during the pixel writing smears the fast scan energy (light and heat) into a more uniform profile. The image of a uniform per-pixel light profile at a modulator array will be at least somewhat rounded by diffraction and aberrations, with the net effect that the fast and slow scan per-pixel energy profiles will tend to converge. Systems with nominally uniform writing spot profiles can be expected to experience reduced nearest-neighbor interactions as compared with the nominally Gaussian writing spots.

The multimode lasing behavior intrinsic to many diode laser sources used in laser thermal printing can also affect both the depth of focus and the energy profile from the focused beam, resulting in degradation in the image quality of the printed pixels. In particular, the multiple modes within the converging light beam have a localized spatial coherence that causes that light to focus differently from the main beam, producing hot spots with different best focus positions and extents. If these hot spots persist long enough and are large enough to modify the local temperature profile, then these especially high-irradiance regions within the writing beam will thermally transfer dye more efficiently than that same amount of power spread uniformly over a larger area of donor. As a result, the image densities within the printed pixel can be nonuniform in a random way. This effect can be mitigated by various optical means, by the removal of higher order time variant modes or by optics that homogenize or diffuse the mode structure.

In Section 3.2.2, the point was made that the tightly focused laser beams should coincide with the media within a depth of focus defined by uniform image density criteria. One notable subtlety is that a focused Gaussian laser beam will interact with the media such that the nominal best focus waist position is shifted within the media. Conveniently, a Gaussian beam, normally incident on a dielectric slab, has the same radius at its narrowest waist as it does in the absence of that slab. In Figure 3.4, the profile of the actual beam waist is represented by the thick, continuous curves propagating from left to right through a material with higher refractive index $n_2$ than $n_1$ of the surrounding air. The solid arcs are segments of the actual phase fronts for...
that laser beam. The dashed curves are the profile that the beam waist would follow if the higher-index materials were removed.

The narrowest waist radius $\omega_0$ is uniquely determined by the local waist radius $\omega$, the local radius of curvature $R$ of the phase front, and the wavelength of the beam $\lambda$, all determined at any single distance $z$ from that narrowest waist along the beam’s propagation direction in a material of a single refractive index:

$$
\omega_0^2 = \frac{\omega^2}{1 + \left( \frac{\pi \omega^2}{\lambda R} \right)^2}
$$

The location of the waist radius along the direction $z$ of beam propagation obeys a similar equation in which the radius of curvature and wavelength are the only refractive index-dependent parameters. The incident beam has an initial radius $R_1$, a beam waist $\omega_1$ at the media interface on the air side, and a resultant radius $R_2$ and waist $\omega_2$ on the side of the medium with the index $n_2$. Because the radii of curvature are perpendicular to the phase fronts and, therefore, can be considered rays of the beam, Snell’s law relates their angles with the optical axis. Likewise, because the local waist just outside the medium $\omega_1$ is identical to the local waist just inside the medium $\omega_2$ by conservation of the beam’s energy, then $\omega_1 = \omega_2$.

Therefore, the radius of curvature must enlarge by the medium’s refractive index upon entering that medium. Thus,

$$
\frac{R_1}{n_1} = \frac{R_2}{n_2}
$$
The relationship between wavelengths of the same beam in two different media is

\[ n_1 \lambda_1 = n_2 \lambda_2 \]  

(3.4)

The reduction of wavelength in a higher-index medium cancels the enlargement of the radius of curvature. As a result, the beam waist maintains a constant narrowest radius \( \omega_0 \), but the refracted beam waist plunges deeper into the higher-index medium than in air, by the ratio of the refractive indices.

\[
z_2 = \left( \frac{R_2}{1 + \left( \frac{\lambda_2 R_2}{\pi \omega_0^2} \right)^2} \right) = \left( \frac{n_2 R_1}{n_1} \right)^2 \left( \frac{n_2}{n_1} \right)^2 \frac{z_1}{n_1} \]

(3.5)

This offset in the position of the beam waist in the laser thermal media can be neglected to first order for donors that are much thinner than the distance from the focusing lens to the beam waist. However, the offset ultimately can affect the laser thermal print quality, in terms of the quantity of donor that is transferred and the resulting print density.

### 3.3 LASER SOURCE CHARACTERISTICS

Most of the laser thermal printer design architectures have employed laser diode arrays, although a few have employed discrete laser diodes, either fiber-coupled\(^{17,18,45}\) or arranged into a multibeam print-head with secondary combining optics.\(^{46}\) The majority of the new solutions in laser beam shaping for printing have emerged from the efforts to control the beam emitted from the laser diode arrays. Diode laser arrays\(^{47}\) have been designed and fabricated in great variety, with arrays comprising various mode structures, including single-mode sources, single-by-multimode sources, and multimode sources. Various gain structures have also been used, including gain-guided structures, index-guided structures, and vertical cavity (VCSEL) structures, while the lasers span an emission wavelength range from the visible to the near IR. Laser thermal printers have been undertaken over a narrower wavelength range, from ~800 to 1016 nm, with the high-power IR laser diode arrays spanning a narrower range (~800–980 nm). These high-power laser diode arrays have proven to be generally robust, with lifetimes in excess of 10,000 h being reported.

The typical high-power laser diode array package (see Figure 3.5) has a compact structure, which provides working access to the emitted radiation, as well as quality electrical and thermal mechanical contact. These laser arrays can be configured in air- or water-cooled packages, as well as stacked to form a 2D array. The laser array itself, whose features are too small to discern in Figure 3.5, is a segmented source, consisting of a series of small, distinct light emitters. For state-of-the-art high-power
arrays, these emitters are multimode sources, which are periodically spaced apart over a substantial distance across the device.

In many of the designs, the lasers and laser arrays are operated in CW, as light sources that illuminate a separate light modulation device. The lasers themselves are thus significantly simplified because they lack the ability to directly modulate the emitted light. This is a particular advantage for laser diode arrays. Otherwise, the individual laser emitters, or groups thereof, must be addressed to provide drive signals on a per-channel basis. Providing individually addressable channels or emitters within a laser diode array is not trivial, not only because of the separation in the electrical pathways that is required, but also because optical crosstalk (phase locking) and thermal crosstalk between the emitters can degrade the quality of the modulation. The use of an external modulator or modulator array has several significant advantages, including the opportunity to optimize the modulation performance and to provide a large number of modulation channels (or pixels). Admittedly, an optical system that employs a modulator external to the laser source is inherently more complicated than a system with direct laser modulation.

High-power diode laser arrays are available at various rated output power levels, including 10, 40, and 80 W, with light emission in the near IR (790–980 nm). Historically, these devices were available from companies such as Opto Power Corporation (Tucson, AZ) and Spectra-Diode Labs (San Jose, CA). Presently, high-power IR laser diode arrays are available from numerous companies, including II-VI Laser Enterprise GmbH (Zurich, CH), Coherent Inc. (Santa Clara, CA), DILAS Diodenlaser GmbH (Mainz, DE), and Jenoptik (Jena, DE). The beam properties of the emitted light in the two directions (array and cross-array) are considerably different, relative to numerical aperture (NA), beam profile, beam coherence, and Lagrange (defined in Section 3.3.2).

3.3.1 LASER COHERENCE AND BEAM SHAPE ISSUES

As an example, an Opto Power OPC-A020 array comprises 19 multimode laser emitters, each 150 μm wide (w), which are spaced apart on a 650 μm pitch (p), for an overall array direction length of 11.85 mm. The large emitter-to-emitter pitch enables these lasers to provide very high output power levels from a very small area,
Laser Beam Shaping in Array-Type Laser Printing Systems

while still minimizing thermal crosstalk effects between emitters. Typically, in the array direction, the light is emitted into a relatively small NA (~0.13 for the A020 laser), but with a very non-Gaussian angular beam profile. As these lasers have a fairly large emission bandwidth ($\Delta \lambda$) of ~3–4 nm for a laser, the output light is nearly incoherent temporally, with a short coherence length $C_L$:48

$$C_L = \frac{\lambda^2}{\Delta \lambda} = 0.2 \text{ mm} \tag{3.6}$$

Of course, compared with an LED emitter with a 40 nm bandwidth and a coherence length of ~15 $\mu$m, these lasers are still relatively coherent. Approximating the array direction beam as an incoherent uniform source, the coherence width (or coherence interval) $C_I$ of these lasers is small compared with the 150 $\mu$m array direction emitter width:49

$$C_I = \frac{2 \times 0.16 \times \lambda}{\text{NA}} \approx 2 \mu\text{m} \tag{3.7}$$

Given the further assumption that the lasers are largely free of filamentation effects, the light emitted in the array direction is spatially incoherent across each emitter. As a result, the overall array direction, near field light profile, across each of the emitters, as shown in Figure 3.6, is relatively flat topped with minimal rippling from intraemitter interference. In many lasers, there is a general roll-off to the array direction light emission profile, with the result that the array beam has both macro- and microspatial nonuniformities, although laser emitters with a generally uniform multimode emission have been reported.50 In effect, in the array direction, the emitters approximate miniature incoherent or partially coherent extended sources, rather than the point light sources that most lasers approximate. Furthermore, as the emitters are not phase-coupled with one another, the light from the various emitters can be superimposed at the modulator without interference and the resulting rippling in the irradiance profile.

![FIGURE 3.6](image)

A measured near-field beam profile for a multimode emitter.
Likewise, Figure 3.7 shows a representative of far-field light distribution for the light output by an emitter in the multimode direction. While the angular extent is narrow (NA \sim 0.07–0.14) and the cutoff is sharp, the profile is not uniform but rather has sharp peaks and is often bimodal with pronounced dip in the center. The doubled-lobed structure is evidence of some near-field filamentation within the laser. The filamentation has a dominant spatial frequency that depends upon how hard the device is pumped, microscopic material parameters (linewidth enhancement factor and nonlinear index), and the stripe width. The dominant spatial frequency Fourier transforms into two lobes in the far field.\textsuperscript{51}

By comparison, the light emitted in the cross-emitter direction is a nominally single-mode (TE\textsubscript{00}) beam that behaves according to the principles of Gaussian beam propagation. Thus, both the near field and far field light profiles have Gaussian beam profiles, rather than the uniform and bimodal distributions seen for the multimode light. The light emitted in the cross-array direction is output over a much larger NA (~0.63), corresponding to a cross-array direction Gaussian beam 1/e\textsuperscript{2} emitting width of $H = 2 \times \frac{\lambda}{\pi \times NA} = 0.85 \ \mu m$. In the cross-array axis, the emitters typically have an epitaxially formed wave guiding structure that supports only one laser mode, effectively forcing diffraction-limited output. By definition, the light emitted in the cross-array direction (laser fast axis direction) of any given emitter is coherent over the beam width (typically approximated by the 1/e\textsuperscript{2} emitting width). Although each laser emitter outputs a coherent cross-array direction beam, there is no common phase relationship from emitter to emitter and, thus, the beams can be combined without cross-array phase-coupling and interference. The spatial coherence of the cross-array light is integrated over the entire array, as further modified by the cross-array smile and limitations from the optics.

3.3.2 Laser Arrays as Light Sources

There are numerous properties of the laser diode array, other than coherence, that must be well understood in order to design a laser thermal printer. In particular,
it is of paramount importance that the light source be well matched to the application; otherwise, the system light efficiency will suffer. In this case, the optical spot at the media and the emission characteristic of the laser must correlate.

In classical optical terms, there are two concepts regarding the constancy or invariance of the propagation of light and the conservation of radiance that apply. An optical source is characterized by both its physical and angular extents. The optical extent can be calculated two-dimensionally, as the etendue (product of spatial and angular emitting areas), or one-dimensionally, as the Lagrange (product of the spatial and angular emitting widths). These quantities can be calculated for a source as a whole, or incrementally for any portion of the source, and then integrated over the entire source. In most optical systems, it is desirable that the etendue or Lagrange (the product of the physical and angular widths of the light) be conserved at any and every optical surface within the system to match the value calculated for the original source.

The conservation of etendue (or Lagrange) is closely related to the law of the conservation of radiance. Radiance is a radiometric term that quantifies the optical power density at a given surface, which is estimated as the optical power divided by the product of the emitting spatial area and the emitting angular area (in steradians). Accordingly, per the law of the conservation of radiance, radiance is conserved or constant throughout an optical system, given that light absorption, scattering, and vignetting are ignored.

In most cases, it is sufficient to estimate the optical power and optical power density (irradiance = optical power per area) at key surfaces throughout a system, and otherwise simplify to tracking the etendue or the Lagrange during the design phase. Because etendue needs to be tracked only in the rare nonorthogonal system, Lagrange is more commonly used. Laser diode arrays are atypical light sources because they have dramatically different Lagrange values in the two meridians (array and cross-array), particularly when the laser array comprises at least one row of single-mode-by-multimode laser emitters. As discussed above, in the array direction, the typical laser array emitter is an incoherent or partially coherent source, and the emitter Lagrange can be estimated as \( L = NA \times w/2 \) (NA \times \text{half width}). In the cross-scan direction, each emitter is nominally a coherent single-mode (TE\(_{00}\)) Gaussian beam light source, and the Lagrange can be estimated as \( L = \omega \times NA = \lambda/\pi \). In use, these values are calculated at the light source and are then tracked through the system, resulting in the desired spot size and light convergence at the target plane. The calculated values need not be absolute, but sufficiently accurate to be useful. As most light sources do not have hard edges to define the spatial or angular extents, but rather fall off according to some gradual profile, it is common practice to estimate these widths at the half maximum or \( \sim 10\% \) intensity levels.

A typical laser diode array, comprising emitters that are multimode in the array direction and single mode in the cross-array direction, is depicted in Figure 3.8. Relative to a single emitter, the array direction corresponds to the junction direction beam \( (\theta) \). In a single-mode laser, the emitted light in the junction direction is highly Gaussian with a modest divergence. However, in the present case of the multimode emitter, only the modest divergence is retained. The cross-array direction of the laser array also corresponds to the cross-junction direction of the laser diode structure.
In the cross-junction direction, the emitted beam is generally Gaussian, with a relatively poor beam quality, and is emitted within a large angular divergence ($\theta_{\perp}$).

As a representative example, a laser array (the OPC-A020) has array direction emitting width ($w$) of 150 $\mu$m, and an array direction NA of ~0.13, and has an emitter Lagrange of $L = NA \times w/2 \sim 9.75$ $\mu$m. The array direction Lagrange for the entire laser array (19 emitters) is, therefore, ~187 $\mu$m, assuming that the array direction optics are designed to not see the nonemitting spaces ($p-w$) between the emitters. The latter goal, of collecting light from the laser array without seeing the spaces between the emitters, can be achieved through the use of an array direction-oriented lenslet array. Conversely, if the light from the laser array is collected with a single lens, rather than with the lenslet array, the array direction laser Lagrange would be fairly large ($L = 0.13 \times 11.85/2 = 0.77$ mm). This difference in the collected Lagrange can bear importance relative to the angular width (NA) or optical efficiency as the light encounters both the modulating devices and the printing media or target plane.

In principle, the Lagrange for the laser array in the cross-array direction is equivalent to the Lagrange of a single laser emitter. As the laser emitters nominally output single TE$_{00}$ mode light as a classical Gaussian laser beam, the cross-array Lagrange is estimated as $L = \lambda/\pi$. Thus, an exemplary laser source emitting 830 nm light will have a cross-array Lagrange of ~0.26 $\mu$m. It should also be emphasized that the cross-array laser light is also typically emitted into a highly divergent beam (NA ~ 0.5–0.6), in contrast to the low divergence array direction beam (NA ~ 0.1).

Thus, it can be seen that the typical single-mode-by-multimode laser diode array has array and cross-array Lagrange values that differ by approximately 700 times. Although both the array and cross-array Lagranges are much smaller than the Lagrange of a modern LED emitter ($L \sim 0.5$ mm) or a xenon arc lamp ($L \sim 3$ mm), the difference between them is, nonetheless, substantial. The entire ensemble of differences in beam emission properties (mode structure, relative coherence, output NA, and brightness or Lagrange) help motivate the very different laser beam shaping optical designs that are employed in the array and cross-array directions of many of the laser thermal printing systems. In general, to design the cross-array optics with accuracy, the standard practices for Gaussian beam propagation must be followed. In many cases where the array direction light is multimode and generally incoherent, classical imaging optics and illumination optics design principles are appropriate. As might be expected, optical systems with these laser diode arrays typically employ
Laser Beam Shaping in Array-Type Laser Printing Systems

numerous cylindrical lens elements so that the array and cross-array light beams can be shaped and directed independently. However, other specialty optics, including fiber lenses and lenslet arrays, are also frequently used in the immediate vicinity of the laser array\textsuperscript{55} and throughout an entire optical system.

### 3.3.3 Other Laser Sources

In the preceding discussion, it has generally been assumed that the laser source is a laser diode array comprising a single row (a linear array) of single-mode-by-multimode laser emitters. Certainly, other laser sources are available and have been used in laser thermal printing systems.

As a simple extension to the presumed laser diode array structure, stacked laser diode arrays are also available, in which a multitude of rows of single-mode-by-multimode laser emitters are stacked in the cross-array direction. Stacked laser arrays are used in laser pumping applications, where the ensemble device is an effective source for high brightness IR laser light. The laser array to laser array spacing is relatively large (e.g., \( \sim 1.8 \text{ mm} \)), which means that the cross-array Lagrange is significantly increased unless cross-array micro-optics, such as a lenslet array, reflective mirror array, or the like, is employed to remove the spaces between the arrays\textsuperscript{56}.

As discussed further below, addressable single-mode laser diode arrays have also been used in laser thermal printer systems to write on the media directly. Lacking an external modulator, such systems can be configured in a straightforward manner, to image the laser array to the media plane at an appropriate magnification\textsuperscript{6}. However, as such a system is susceptible to the failure of one or more laser emitters, alternative system configurations have been developed\textsuperscript{57} to provide emitter redundancy, even with an addressable laser diode array. In this latter case, a laser diode array comprising a linear arrangement of single-mode array direction emitters was constructed, wherein the laser emitters were arranged in addressable subarrays\textsuperscript{58}.

One exemplary IR (850 nm) laser diode array of this type consisted of 160 single-mode diode lasers, which are gathered into 10 groups or channels, separated by a 250 \( \mu \text{m} \) space between groups. Each channel or subarray is composed of 16 single-mode diode lasers spaced apart on a 50 \( \mu \text{m} \) pitch so that a subarray spans 750 \( \mu \text{m} \). Each of the 10 channels is modulated as an ensemble by its own current driver. The individual single-mode laser emitters are spaced far enough apart that the emitted beams are not coherent (phase locked) one to another. The beams can be combined within the optical system without incurring significant interference effects.

With this type of laser array, the Lagrange per emitter is nominally identical in the array and cross-array directions, at \( L = \frac{\lambda}{\pi} = 0.85 \frac{\mu \text{m}}{\pi} = 0.27 \frac{\mu \text{m}}{\pi} \). However, in the array direction, there is a Lagrange per subarray (16 emitters) of 4.3 \( \mu \text{m} \), as well as an overall potential array direction Lagrange for the entire 160 emitters (spaces removed) of \( \sim 43.3 \mu \text{m} \). In practice, the array and cross-array beams may not have the same precise emission characteristics (such as NA). In particular, the cross-array light may be index guided and thus more tightly confined, whereas the array direction light may be only gain guided and may emit from a larger active region at a smaller NA. It can again be anticipated that it might be important to use array direction optics (such as a lenslet array) that omits the spaces, rather than optics (such as a single combining lens)
that sees the whole laser array. As previously, the array and cross-array direction laser beams possess significantly different properties, thus imparting comparable differences to the laser beam shaping optics employed in the two directions.

3.4 ARRAY AND CROSS-ARRAY OPTICS

In the cross-array direction, the typical design intent is to collect the light from the laser array, transmit the beam through the array direction optics with minimal cross-talk effects, and focus the beam onto the media plane. Typically, the printing application defines the desired spot size relative to the pixels (or dpi) required. The incident beam’s NA is typically determined by the depth of focus required by the media handling system. In the case where an external light modulator is used, there may be further significant system constraints imposed on the cross-array beam size and NA as part of optimizing the light to the modulation device.

The cross-array optics, which are only shown in the most basic way in Figure 3.9, typically include a fiber lens and one or more cross-array lenses. The fiber or rod lenses are typically microlenses with very short focal lengths (~100–200 µm), which both allow spherical aberration to be minimized, enhanced by special corrections designed into the lenses. For example, the fiber lens or fast axis collimator (FAC) can be a gradient index cylindrical microlens from Doric Lenses Inc., an aspheric microlens from LIMO GmbH, or a hyperbolic cylindrical microlens from Blue Sky Research, which provide further aberration control. These lenses are typically employed to collimate the cross-array light beams, although they can be used to reduce the laser divergence to a lesser extent (to less than full collimation). Use of a rod lens also allows the high NA cross-array light beams to be quickly controlled before the propagating light beams become awkwardly large. Moreover, the cross-array direction optics can also be packed in close to the laser array, helping to reduce the overall size of the system. Concepts for self-registering microlenses have also been developed to enable light collection from a laser array.

---

**FIGURE 3.9** Laser diode array package with integrated cross-array and array optics. (From U.S. Patent 5,212,707.)
The array direction lenslet array or slow axis collimator (SAC) is a monolithic array of cylindrical lenses, molded from fused silica or Ohara S-TIH53 glass. The lenslet array is most commonly anamorphic and operates only in the array direction light, but arrays with integrated cross-array direction power are also available (e.g., the LIMO GmbH FAC-SAC collimation modules).

### 3.4.1 Laser Smile Error

Most simply, light transfer from the laser array to a modulator array or the media plane can be accomplished by imaging the emitting surface to the target plane with the two planes conjugate to each other. In the direct printing systems, the laser emitters are imaged directly onto the media plane, and thus the cross-array laser characteristics directly affect image quality. In other systems, in which the emitted beams are intermingled, the cross-array laser characteristics can have a less direct impact on image quality but are still significant with regard to system light efficiency, modulation contrast, and depth of focus.

Generally, the cross-array laser beam shaping optics comprise an arrangement of cylindrical lenses, except that the problem of laser array smile (see Figure 3.10) is an added complication. In the prior discussions of the cross-array properties of the laser diode arrays, the laser emitters were considered to be identical in emissive properties, having a nominal emitter Lagrange of $\lambda/\pi$ and located in a perfect linear arrangement. However, as can be seen in Figure 3.10 (which is a near field projected image), the laser emitters are typically not located in a perfect linear arrangement, but are offset from the ideal, usually with a slowly varying pattern error spanning a few microns. The net effect of this diode laser fabrication error is that not all laser emitters on the same substrate emit beams from the same plane. Most simply, smile is a lack of straightness in the array over its length.

Certainly, an uncorrected smile error can manifest itself as a printing artifact or inefficiency. In the printing systems where the laser emitters are mapped directly or indirectly to the media to form printing spots, smile can create directly viewable artifacts. Most directly, the inaccuracy of the diode laser light source positions is projected onto the medium as an arch in the sequence of writing spots, which appears as a smile. Alternatively, a smile error creates banding when a tilted print-head is used, as the distance or pitch between emitters (writing spots) is no longer constant. By comparison, in many of the printing systems involving flood illumination of a modulator array, the emitted beams are intermingled, as an uncorrected smile error can cause the cross-array Lagrange to be enlarged significantly. In effect, several microns of smile error across the laser array can increase the cross-array Lagrange by 10 times or more from the nominal Gaussian $\lambda/\pi$. This increase can

![FIGURE 3.10 A line of printing spots exhibiting laser smile error.](image_url)
significantly impact coupling through a modulator (modulation contrast, efficiency) and the spot formation at the media (depth of focus, spot size).

Laser array manufacturers have improved their ability to control or reduce smile error, and laser bar technology based on hard-soldered CuW submounts can deliver out-of-factory smile error of 1 μm or less, and most manufacturers offer low-smile packages. For example, devices with smile values of only 0.3–0.4 μm over a 5 mm bar length are reasonably available. Laser array smile develops in the fabrication process as the mechanical stress across the array changes. Most typically, smile is exhibited as an arched pattern of emitters, although other more complicated pattern errors (“s” or “w”) can occur. Assuming that the supply of laser arrays have smile errors that follow a simple “s”- or “c”-shaped arc, the smile error can be compensated for by bending the fiber lens to a matching arc.59,61 The resulting line of collimated laser beams travels in parallel to the optical axis but with slight offsets. Cylindrical power crosstalk or skew ray effects are negligible because the bent fiber lens has a few microns displacement over a 10–15 mm laser array length.

### 3.4.2 Laser Smile Correction

Despite these gradual improvements in laser array technology, the system impact of smile error is sufficiently damaging that numerous means5,61–64 for smile correction have been developed. Smile correction at or near the fiber lens is necessary for the optical systems that image intermingled beams,9,11,21 as the beam deviations incurred by the emitter offsets are overlapped and no longer separable once the beams have been intermingled.

There is greater freedom to develop smile correctors for optical systems that image the laser emitters, either directly45 or indirectly,7,57 to the media. Exemplary smile correctors have also been developed that can correct most, if not all, of the smile in an array, independent of the shape of the smile error across the array. One such smile corrector,62 shown in Figure 3.11, comprises a series of glass plates inserted into the optical path in collimated space. By properly tilting each of the plates, the position of that beam at the pupil is shifted to correct the smile at the medium’s plane.

Other exemplary smile correctors allow individual cross-array lenses62,63 or mirrors64 to be adjusted on a per-emitter basis, adjusting the various beams into coplanar or common optical planes. These latter methods are limited to the practical
dimensions of the beam correcting offset mechanisms, and thus work well with laser arrays that have laser subarrays or large area multimode emitters positioned at large pitch distances. Alternatively, optical aberrations, either natural or induced, have been used to broaden the apparent cross-array emitter size, thereby desensitizing the system to smile error but at the cost that the cross-array Lagrange has been increased.

Fast axis collimators, as manufactured, can suffer from imperfections at the submicron level. Taken together, misalignment errors, bar smile, and facet curvature introduce optical errors including wavefront distortion, wavefront curvature, and pointing error. However, these errors can be compensated with refractive phase plates before the wavefront forms a caustic. In the simplest form, when only pointing (smile) correction is required, the phase plate can be made in the form of either a microprism array or a continuously varying wedge surface. For example, PowerPhotonic Ltd (UK) offers a range of smile correction phase plates that correct for imperfections in fast axis collimation using continuously varying wedge surfaces that correct for the postcollimation pointing of light from each emitter. These phase plates correct for a parabolic-type smile error, expressed as P-V pointing error of 0.5‒3.0 mrad, and are available in increments of 0.5 mrad. Also, these correction phase plates (see Figure 3.12) are available integrated into the SAC, providing a single element to be aligned during the laser bar microlensing process.

3.4.3 Operating Dependence of Laser Smile

Notably, laser smile also depends upon external conditions, including device mounting and temperature. In the latter case, smile correlates with laser current and smile can increase by multiples of 100 nm, going from threshold to a nominal current. Lasers can be scanned and binned depending upon the type of the smile (C, S, or W) and the P-V smile value. Each emitter can then be assigned a single average phase compensator.

**FIGURE 3.12** Phase plate smile corrector. (Courtesy of PowerPhotonic Ltd., Fife, UK.)
In addition, in printing applications, laser diode bars often operate at different currents depending upon the sensitivity of the printing plate that is imaged. It is important to note that the smile of the laser bar has a temperature dependence. As shown in Figure 3.13, in the case of conductively cooled bars, laser smile can correlate with the laser current. Thus, increasing the laser current will increase the output power, but it will also increase the spot size in the fast axis direction through increased bar smile.

**3.4.4 Optical Alignment Issues**

Typically, laser thermal printing systems have rather different alignment tolerances for the constituent optics in the array and cross-array directions. This generality can break down, depending upon the system configuration.

In cases where the laser array is directly addressed and directly imaged to the media with largely spherical optics, the spot-to-spot pitch will be largely determined by the laser array fabrication process, and the array printing (slow scan) and cross-array printing (fast scan) directions will generally see similar optical tolerances. The fast scan motion of the drum or media will tend to blur the spot in the cross-array direction, potentially easing those tolerances. If the print-head is integrated as a closely packed array of spots, then there will be swath-to-swath positioning tolerances, driven by the need to minimize a visual artifact known as banding.

Should the laser array employ laser emitters that are single mode by multimode, the laser beam shaping optics will typically be anamorphic, and will include a variety of cylindrical optical elements. Relative to the laser arrays, the single-mode direction typically corresponds to the cross-array direction, while the multimode emitter orientation corresponds to the array direction. The asymmetries naturally align, such that the array direction of the laser array corresponds to the array direction of the printer. It can be understood that these systems are generally very sensitive to crosstalk of the array beam into the cross-array direction. For example,
a slight $\theta_z$ (about the optical axis) tilt of an array direction cylinder lens will transfer optical power into the cross-array direction, which could cause dramatic changes in the beam propagation (spot size in critical planes), as well as a rotation effect. Likewise, a slight $\theta_z$ tilt of a cross-array direction cylinder lens will likely have a more dramatic effect on the cross-array beam propagation than on the array direction light propagation.

Not surprisingly, although the rotational alignment tolerances for the cylindrical lens elements can be as much as $\sim 10$ arc/min, tolerances of $\pm 2$ arc/min are not unheard of. By comparison, the spatial mechanical alignment tolerances for the cylinder lens elements can be a relatively relaxed $\pm 50$ $\mu$m, as compared with the submicron positional tolerances seen in other laser applications.

### 3.5 DIRECT LASER TO MEDIA SYSTEMS

As a design architecture for a multichannel laser thermal printer, the system configurations in which a series of discrete laser sources correspond directly to a series of laser printing spots provide potentially the most compact designs with the lowest cost structures. In many cases, the laser emitters are directly addressable with image data, and the laser emitters are mapped to the media. Alternatively, the laser beams can be routed to the media indirectly, by means of optical fibers. The laser sources can also be equipped with individual external modulation devices before being mapped to the media. In any of these cases, the resulting multichannel laser system is vulnerable to the degradation or failure of individual laser sources, although some of the systems offer the potential to field-replace failed lasers. Although this discussion is targeted at linear printing systems, primarily using one-dimensional (1D) laser arrays, system concepts have also been developed for writing with 2D arrays of laser diode sources.

#### 3.5.1 LASER EMITTERS MAPPED TO THE MEDIA

Aside from contact printing, wherein an addressed array of light sources would print image pixels without any intervening optics, the simplest and most obvious architecture for providing a laser thermal printer is to image an array of directly addressable laser diode emitters to the media plane. In one exemplary system developed by Eastman Kodak Company (shown in Figure 3.14), a linear array of laser diodes is monolithically integrated on a single semiconductor substrate, but is individually addressable and independently controllable from each other. The simplified optical system uses spherical optics to image the laser array directly onto the media, such that each laser diode corresponds to a pixel in a line on the print. Heat is generated on a per-pixel basis, resulting in dye evaporation and transfer from the donor to the receiver. A similar system is described for high-resolution electrostatic printing, in which an array of surface emitting lasers is imaged in magnified fashion onto the media. Both of these systems are susceptible to a variable response from laser emitter to laser emitter across the laser array. However, while emitter variability can be potentially corrected for via a calibration process, any outright emitter failures would provide likely uncorrectable line artifacts.
Many of the optical systems discussed below are motivated by the perceived need to desensitize the printing system to laser emitter variability or failure. However, even within this class of simplified systems that use directly imaged laser arrays, source failure was taken seriously. In one case, the multitude of laser emitters are driven as a group, and the light from the entire array is directed onto the media to form a single writing spot. The emitter redundancy is provided at the cost of a low printing throughput (speed and resolution). More recently, it has been proposed that the diode laser arrays are sufficiently robust that laser emitter to media-mapped printing systems can be undertaken without the need for redundancy.

An exemplary optical system, developed by Scitex Digital Printing Inc. for an image setter (shown in Figure 3.15), collects light from an addressable laser array,
Laser Beam Shaping in Array-Type Laser Printing Systems

consisting of a multitude of single-mode-by-multimode emitters. The system provides an anamorphic optical system with a cylindrical rod lens and a spherical printing lens, such that a row of nominally circular 20 µm printing spots is provided. As in many later systems, the printing lens is double-telecentric (telecentric in both object and image planes) so that the printing spots have a common depth of focus across the drum. In the cross-array direction, where the narrow, single-mode emitter is to be mapped to the target of a 20 µm width, the working distance between the emitter and the rod lens is controlled to provide the desired width at the media plane as a defocus spot width. Depending upon the cross-array NA needed at the media plane, this system potentially requires tight control on the drum and media placement. Otherwise, motion of the media through a defocused beam may cause undesired spot size and shape variation.

As another alternate system,68 shown in Figure 3.16, the light from the laser diode emitters of a nonaddressable laser diode array source is mapped to an external spatial light modulator array. This system, which was developed by Barco Graphics, employs array and cross-array micro-optics, including a rod lens and a lenslet array. In the array direction, the laser emitters are mapped (either far-field projections or near-field images) to the modulator array such that each emitter illuminates one of a series of adjacent regions of the modulator array. In the cross-array direction, the rod lens works with other optical elements to image the beam directly onto the modulator array. The modulator array is, in turn, imaged onto the media by a printing lens (not shown). This system is nominally a critical (or Nelsonian) illumination system69 in which the illumination source is imaged onto the object, and it is thus sensitive to the detailed behavior of the source. While outright failure of the laser diode emitters across a laser diode array may be a diminishing concern, output variability, either emitter to emitter, or as a light emission profile (near field or far field) across the emitters, could detrimentally impact either of these systems.

3.5.2 Multiple Discrete Lasers Mapped via Free-Space Optics

Although many of the laser thermal printer designs have employed high-power laser arrays, either directly addressed or indirectly modulated, some viable systems have been provided that employ a series of discrete laser diode sources. The Polaroid Helios™ systems46,70 are an example of a design approach in which a series of

![Diagram of laser printing system with the laser emitters optically mapped to provide adjacent nonoverlapping illumination of a modulator array. (From U.S. Patent 6,356,380.68)
free-space propagating beams are combined to form a print-head that directs the printing spots onto a media mounted on an external drum. As with many of the other laser thermal media, the Helios media, which comprises a light-sensitive carbon particle layer sandwiched between donor and receiver polymer sheets, is a threshold media. To accommodate the image quality needs of the initial Helios medical imaging market, the $8 \times 10$ in. monochrome prints were printed with pixels having grayscale (256 levels) modulation. The Helios system provided the grayscale modulation by writing each pixel with a halftoning process in which each pixel, consisting of a series of subpixels, is written by a combination of four independently modulated laser diodes.

The basic Helios system, as shown in a simplified form in Figure 3.17, comprised four laser beams that were combined via a multifaceted mirror to subsequently follow parallel optical paths through the remaining optics (see Figure 3.18) that form the printing spots on the media. The mirror array provides two offset opposing facets that redirect two of the laser beams (Lasers 2 and 3) into parallel paths. The third beam (Laser 1) passes through a gap between the two opposing facets, while the fourth beam (Laser 4) deflects off a tilted mirror located in the gap between the two opposing facets. This system provided a unique configuration of four printing spots, with each printing subpixel structure within the overall $90 \times 90 \mu m$ pixels. As shown, two elongated spots lie offset along a common axis, a third elongated spot is horizontally centered to the first two spots, but vertically offset, and the fourth spot has a smaller size and is positioned similarly to the third, but with the opposite vertical offset. The fourth and smallest beam is designed to have about one-seventh of the energy of the other three beams so that accurate tone scale reproduction could be provided for the highest density regions of the print. Although Figure 3.17 does not show this detail, the third beam is not only vertically offset from the first two, but it also has some horizontal overlap with these beams as well. The combination of offset and overlap reduces print artifacts in the written pixel that would originate with irradiance variations from diffractive interactions at the mirror facet edges.

The four laser diode lasers are high-power (500 mw) IR (820 nm) single-emitter lasers, with single-mode ($\sim 1 \mu m$ wide, $1/e^2$ NA $\sim 0.5$)-by-multimode.
Laser Beam Shaping in Array-Type Laser Printing Systems

(≈100 µm, NA ≈ 0.07) emission structures. The laser beam shaping optical systems (see Figure 3.18), which are largely identical for the four lasers, begin with a fast (NA ≈ 0.55) molded glass aspheric spherical collimating lens. Ultimately, the desired elongated printing spots provided at the media plane are ≈34 µm long × ≈3 µm wide, with the small spot being only ≈5 × 3 µm in size. The focusing objective, provided to form the four spots onto the media, is a similar lens to the collimator and had a 0.47 NA. Notably, the combined system requirements of subpixel grayscale printing define this system to be fast (high NA) at the media plane and able to image the small printing spots. As a consequence, the depth of focus required at the media plane is short. The system is also required to present the printing beams telecentrically to the media plane, such that the writing beams are parallel to each other as well as perpendicular to the media. The telecentricity requirement is more severe in the horizontal direction (multimode axis) than in the vertical direction, because the scanning motion of the writing spots across the media relaxes the tolerances in the vertical (or slow scan) direction.

In this system, the printing spots are formed by imaging the laser emitters onto the media plane. Thus, the optical system must provide a differential laser beam shaping, such that the cross-array beam is ultimately magnified by about three times, while the emitters are ultimately demagnified by about three times in the multimode emission direction. It is also desired that the NAs in the two meridians be nearly equal at the media plane. As a result, an ≈8 to 9:1 anamorphism is required somewhere within the beam shaping optics.

FIGURE 3.18 The Helios optical system from Polaroid, with four beams combined to form a printing spot with subpixel addressing.70 (Courtesy of Polaroid.)
As shown in Figure 3.18, prior to the faceted mirror array, each of the four laser beams encountered its own beam shaping illumination optical system, comprising the collimator and a three-element beam expander. These illumination systems provide magnified intermediate real images of the laser emitters in both the multimode and single-mode directions. As the beam expanders receive collimated beams and output beams that focus to about 10 times magnified images of the emitters, the beam expanders are nearly afocal (similar to the classic element Galilean beam expander). The illumination systems are arranged radially about the mirror array, with the magnified real images of the laser emitters nominally imaged onto the mirror array facets. The mirror facets act as field stops to control the array direction sizes of the final emitter images, thereby desensitizing the system to illuminator magnification variations. The four beams are redirected by the mirror array such that four nominally parallel beams propagate downstream toward the focusing lens.

Before reaching the focusing lens, the four beams travel through a common anamorphic collimator comprising two crossed cylinder lenses, which is used to equalize the printing NAs to the media plane. A short focal length, positive cylinder lens is located close to the mirror array to collimate the high NA light in the cross-emitter (single mode) direction. A long focal length, positive cylinder lens is located closer to the focusing lens to collimate the light in the slow NA (multimode emission) direction. The final collimated beams are presented to the focusing lens, which can be equipped with an autofocus mechanism. Taken as a whole, the Helios system anamorphically applies Gaussian beam propagation design to the cross-emitter direction, and imaging optical design in the array direction. The array direction system uses critical illumination, with the source profiles ultimately imaged onto the media, which makes the printing sensitive to the array direction near field emitter light profiles. Polaroid addressed this issue by developing laser diodes with more uniform laser near field profiles than were commercially available.

While the illumination systems for lasers 1 to 4 are nominally identical, the illumination systems for lasers 2 and 3 are the only ones that are actually identical, and the illumination systems for lasers 1 and 4 are provided with prismatic wedges. These wedges provide telecentricity correction, as well as coma correction, needed by the vertically offset laser beams (lasers 1 and 4) that traverse the short focal length first cylindrical collimator in off-axis positions. In the case of laser 1, a pair of prisms (BK-7 and SF-1) is used, while a single prism and a mirror facet angle adjustment are used for laser 4. As laser 4 is provided with an identical 100-μm-wide emitter to that of lasers 1–3, and the printed spot is to be reduced in size (5 vs. 34 μm), the laser 4 beam must be vignetted somewhere in the optical path. This can be accomplished by masking the laser 4 mirror facet, or by reducing its size.

The Helios system underwent several generations of change, first to use higher power lasers and then with improved designs that enabled more printer features and greater throughput on larger media. In one generation, the printer comprised eight laser diodes, arrayed about a multifaceted mirror, to form two adjacent writing pixels, each with the four beam subpixel writing spots. As the multifaced mirror of this later system is cut from a monolithic surface, it is much easier to fabricate than its predecessor (see Figure 3.17). In this system, the anamorphic optics (a cylindrical microlens for the cross-emitter fast axis, and a secondary cylinder lens to correct
Laser Beam Shaping in Array-Type Laser Printing Systems

The complete illumination systems, including spherical lenses, provided magnified (48× and 6.6×, respectively, for the multimode and cross-emitter directions) real images of the laser emitters onto the mirror facets. As before, the mirror facets both redirect and truncate the beams to the desired sizes before the eight laser beams are focused onto the media by a two-element objective lens system. The Helios print-head technology has been used in other applications, including image setting, and as a high-power pumping source for fiber lasers.72,73

3.5.3 Array Printing with Discrete Laser Optical Systems

The Polaroid Helios system is an example of a laser printer in which assemblies of discrete lasers have been used to assemble laser thermal printing heads. The Helios system used a complex optical path, partly because of the subpixel structure but also because of the common free-space optics used to focus the light to the media. As an alternative, Presstek LLC (Hudson, NH) developed a series of light engines in which each of the directly addressed discrete lasers had its own optical path to collect and focus light onto the media. An extended laser printing array is formed from an ensemble of lasers and associated optics assembled across the length of the printing drum. This Presstek print-head has been successfully used in numerous graphics applications, such as CTP, computer-to-proof, and direct on-press imaging, with the Heidelberg Quickmaster DI printing press being a notable example.

This approach has the virtue that the laser beam shaping optical systems are inherently simple. In one configuration, as shown in Figure 3.19, FIGURE 3.19 Printer configuration with a synthesized laser array having fiber-coupled lasers. (From U.S. Patent 5,351,617.17) the light from an IR laser diode is collected by a collimating lens and then focused onto the input end of an optical fiber by a coupling lens to form a fiber pigtailed laser unit. The light traverses the length of the optical fiber, and the fiber output light is collected and focused onto the media by a similar two-element lens output optical system. Standard optical communications connectors, such as an SMA connector, can be used to mate the optical fiber to the output optical system. Preferably, the laser emits light with a small divergence (NA < 0.3), and the finer NA is likewise limited, so as to maximize the depth of focus of the focused light at the media. As is typical in the laser thermal systems, the laser emitter outputs light with both a low NA and a large NA (>0.3). To compensate, the fiber input optical system could also be equipped with a divergence reduction cylinder lens (not shown), which is located prior to the collimator, and which works on the fast axis light. Depending upon the design, this
printer can produce printed spots between ~12.5 µm and 50 µm in size. Alternatively, to avoid the light loss incurred by coupling to the optical fiber, as well as any optical noise from fiber bending or reflection-induced mode hopping in the laser, the optical system can be configured to have the input optics focus the light directly onto the media, rather than into an optical fiber.

As shown in Figure 3.20, a full printer is achieved by arraying a series of laser optical systems across the length of the drum. Each laser optical system is responsible for printing its image pixels within its respective portion of the drum, as the drum is rotated and the print-head is moved laterally. The system places a premium on the optomechanical alignment tolerances between the series of adjacent laser optical systems being maintained over the length of the drum. Similarly, it can be difficult to control focus across the synthesized laser array, as the focal distances are not defined with one mechanical reference (as with the fiber pigtailed print-head discussed in the following section) but depend upon the fabrication and calibration of the individual laser optical systems.

Further improvements have been made to this approach, including the use of an annular baffle within the fiber output optics to limit ghost reflections and depth of focus loss caused by high-NA light emerging from the optical fiber. In addition, a controlled angle diffuser can be inserted prior to the baffle to smooth out hot spots in the multimode light that emerge from the optical fiber so that more uniform image pixels are printed, thereby improving the image quality. Smoothing out of the sharp multimode light peaks can also improve the depth of focus to the media plane, although the beam Lagrange is presumably increased. As previously noted, this system can be

FIGURE 3.20 A digital offset printing press using Presstek’s laser thermal imaging head technology. (Courtesy of Presstek LLC, Hudson, NH.)
sensitive to focus variations across the printing head, which can be caused by both variations in the laser optical systems and misalignment of the printing head to the drum. To address this variability of the spot focus from one laser optical system to another, provision has been made to individually shim each of the respective output optical systems\textsuperscript{74} in order to adjust the focusing distance out of each assembly. With this approach, the focal position for each channel can be tuned to reach the needed working distance, although a small variation in the printing spot size may result, as the conjugate distances (fiber to focusing lens to the drum) are being changed.

A novel design alternative to this system, as shown in Figure 3.21, has the directly addressed IR laser acting as a pump laser to an external laser crystal.\textsuperscript{75} The 808 nm pump laser light encounters a cylindrical microlens provided for divergence reduction and a spherical focusing lens, which together focus the pump light onto the end face of the laser crystal. The laser crystal, which may be a Nd:YAG crystal, for example, produces a low-NA single-mode $\text{TEM}_{00}$ 1064 nm output beam, which is focused on the media by a focusing objective lens. The reduction in the beam divergence, compared with the original pump source, more than compensates for the power lost in wavelength conversion, thereby providing an overall increase in brightness of the light available for printing. Provisions are also made to enhance the response time of the laser crystal, for optimizing the pulse width to control the shape of the printing spots, and to optimize the thermal and mechanical mounting of the crystal in order to minimize printing spot size variation.

Presstek developed another print-head technology,\textsuperscript{45} branded under the ProFire trade name, which uses a series of IR laser diode sources, each containing a laser driver board and a laser diode array that provides four uniquely addressable laser beams. Each laser emitter is optically coupled to a corresponding optical fiber, having a 60 $\mu$m core and a 0.12 NA. The light output from each group of four optical fibers is then imaged onto the media by a single lens assembly to provide four writing channels. This system provides 21 $\mu$m laser spots to the media, enabling 2540 dpi plate printing.

\subsection*{3.5.4 Fiber Array Print-Head}

Compared to many of the prior systems, having laser emitters mapped directly to the media plane, an alternative, highly integrated optical fiber print-head was developed.
by Eastman Kodak Company for the KODAK APPROVAL Digital Color Proofing System. This print-head provides a compact optical head with replaceable individual laser diodes. These systems use laser thermal technology to image cyan, magenta, yellow, and black dyes onto an intermediate sheet that the customer laminates to paper stock. Color images are printed on a press using cyan, magenta, yellow, and black inks. This process may be replicated on a press by imprinting more or less ink to create the tone scale. The high writing resolution of laser thermal technology does an excellent job of simulating the halftone printing process.

The first fiber array print-head was developed using a series of butt-coupled fiber pigtailed diode lasers individually spliced to corresponding print-head single-mode optical fibers (5 \( \mu \)m core), where the print-head optical fibers were brought together in a pattern of adjacent V-grooves. The fiber exit faces were reimagined onto the media by a print lens to provide an array of printing spots.

In order to reduce the spot pitch (increase the optical fill factor), the optical fibers are progressively etched down from the initial 125 \( \mu \)m diameter cladding, to a mere 18 \( \mu \)m diameter. The reduced optical fibers were then assembled into the V-grooves, which were etched into crystalline silicon, and held in place with ultraviolet (UV) curing cement. The V-groove base started at the input end with 250 \( \mu \)m pitch V-grooves and, through a series of progressively smaller V-groove structures, reached the output end with 20 \( \mu \)m pitch V-grooves. The optical fill factor of the print-head could be further increased by tilting the print-head or by interleaving the scan lines, or by doing both simultaneously. Unfortunately, the fusion coupling of the fiber pigtailed laser diodes to the print-head fibers both reduced the system light efficiency to \( \sim 10\% \) and caused channel output power instability.

The APPROVAL Digital Color Proofing System print-head, which has been built-in 30-channel and 64-channel versions, uses a similar architecture, except the single-mode lasers and single-mode optical fibers were replaced with multimode lasers and multimode optical fibers, and dummy channels were added to improve printing uniformity. Figure 3.22 shows a sketch of the optical path of a fiber V-groove printing system. Each diode laser source comprises an array of high-power 830 nm laser emitters that output single-mode-by-multimode light. This light is coupled by a cylindrical lens into the individual multimode optical fibers (NA \( \sim 0.24 \)) to yield fiber pigtailed lasers with \( \sim 400 \) mW output per fiber. Although the fiber supports 0.24 NA light, \( \sim 90\% \) of the coupled optical power is contained within a generally Gaussian beam with NA \( \sim 0.12 \). The pigtailed optical fibers are coupled into the print-head optical fibers (also NA \( \sim 0.24 \)) by means of standard industry ST connectors, which have a high positioning accuracy. To further enhance the

![FIGURE 3.22 Printer configuration with a laser array synthesized from discrete fiber-coupled laser diodes and a V-groove fiber mount. (From U.S. Patent 4,911,526.)](image-url)
coupling reliability, the pigtailed fibers can have a smaller core (50 \(\mu\)m) than the print-head fibers (52 \(\mu\)m).

The multimode print-head optical fibers are glued into V-grooves etched in silicon\textsuperscript{76,77} at 130 \(\mu\)m spacing between centers. The end face of the V-grooves, as shown in Figure 3.23, is polished to provide a smooth and coplanar output surface from which the printing light beams exit the fiber array. A printing lens, working at a demagnification of 2.2:1, images the array of fibers onto the drum, where the donor is mounted over the intermediate. In one version of the system, the printing lens had an acceptance NA at the fiber of 0.12, with the result that the higher-order, large NA light overfilled the print lens, and is thereby clipped. As it operates at a modest magnification, the print lens\textsuperscript{79} supports relatively large fields and NAs at both the object [fiber array (\~2 mm field and \~0.12 NA)] and image planes (\~1 mm field and \~0.264 NA). The integrated print-head, comprising the assembled V-groove fiber array and the print lens, writes swaths of image data along a nominal helix spiral pattern as the head is moved laterally across the drum. This print-head could also be tilted at an acute angle to increase the apparent print-head resolution by compensating for the gaps between the optical fiber cores.\textsuperscript{34} The fiber-to-fiber placement error can be measured, as can the spot-to-spot spacing, in both the along-array and cross-array directions. The array is tilted to achieve the desired spot-to-spot spacing. Adjusting the angle of the array compensates for variations in lens magnification. The data for each channel are digitally delayed to align pixels to a line normal to the fast scan direction on the proof. An autofocus mechanism can be used to ensure optimal focus of the writing spots on the print media.

As might be expected, this system is sensitive to fiber noise. For example, movement of the fibers as the print-head traverses the drum can launch light into higher-order modes. Likewise, energy can be scattered into higher-order modes as the result of fiber-to-fiber irregularities, crimps, sharp bends in the path, and so on. Laser mode hopping, which is of direct or indirect lasing instability, can cause
similar effects. As higher-order modes typically comprise high NA light, the relatively large fiber NA (0.24) used in this system means that light launched into those modes is not automatically attenuated. At the cost of a reduced light efficiency, the original 0.12 NA print lens used vignetting to remove these unstable higher-order modes. Alternately, the system can be configured with a faster printing lens [NA (~0.48) to the media plane] that allowed most of the higher-order-mode light (and power) through to the media plane.

Noise from higher mode structure, whether from fiber movement or mode hopping, can be problematic and interactive. Mode structure noise rotates and changes the structure within the spot, resulting in a different line trace within the image. Furthermore, as the higher-order modes are typically large NA modes, they provide a smaller depth of focus and thus increase the system sensitivity to focus position. Finally, noisy or time-variant higher-order modes can also make the light profiles within the printing spots variable, potentially affecting the final print uniformity.

Laser mode hopping can be minimized with careful coupling of the optical fiber to the diode laser. Optical reflections returning to the diode laser cause mode hopping, changing the output power and wavelength. Optical reflections returning to the diode laser cause mode hopping, changing the output power and wavelength. Multiple diode laser channels reduce the sensitivity to individual laser noise, as each channel may be considered an uncorrelated random noise source. The multiple diode laser elements that constitute each laser source further reduce the individual channel noise. Images created using a single laser can channel exhibit artifacts as a result of laser startup transients caused by changes in diode laser temperature, optical power, wavelength, or mechanical position. Additional channels break up the appearance of these artifacts. Modulation of the laser with image data is another method of breaking up the artifacts in the prints and making them less noticeable.

3.5.5 Fiber Array Print-Head with Addressable Laser Arrays

Although the fiber pigtailed multichannel print-head described in previous Section 3.5.4 is technically straightforward, the total cost of the fiber pigtailed laser print-head becomes excessively expensive as the number of channels increases. The electronics cost to support the print-head also grows rapidly as the number of channels increases. About 30 fiber pigtailed channels is a reasonable compromise because the ratio of the print-head cost to total system cost is less than 20%.

One approach to reduce the cost of the fiber array head is to use an individually addressable laser diode array (IALDA) coupled to a fiber array. As an example, CreoScitex Corporation developed a system in which each independently addressable laser emitter is coupled to an optical fiber. The print-head routes an input bundle of optical fibers to an output optical bundle via a connector board, and further provides two-fiber alignment V-groove assemblies, one at the IALDA side and one at the imaging side, as illustrated in Figure 3.24. Despite having a provision for spare emitters, printers that use direct imaging of IALDAs found only modest implementation because of the limited redundancy and relatively high cost of service.

Notably, however, for laser array to fiber array coupling, this print-head used a customized version of LIMO monolithic fiber-coupling lens, having a common fast axis (FA) lens on one side and slow axis (SA) lenslet array on the other. As shown
in the cross-sectional views of Figure 3.24, this lens is highly anamorphic, with the image plane of the cross-array or FA lens and the focal plane of the array direction or SA lens coinciding at the fiber position. The exit NA is intended to be equal in both directions, and the spot size in the SA direction is then meant to be approximately 10% smaller than the fiber core diameter.

### 3.6 MODULATED SUBARRAY LASER PRINTING

Although the system of Figure 3.22, with multiple individually fiber-coupled lasers, and the system of Figure 3.24, with an addressable laser array with fiber-coupled emitters, both provided laser to pixel addressing, as they both lack redundancy, they thus require laser substitution to correct a failed emitter. As an alternative approach to reducing the print-head cost, a print-head architecture was developed in which the laser array is provided with multiple addressable groups of single-mode diode lasers on the same substrate.\(^\text{58,82}\)

The associated optical system\(^\text{7,82}\) provides a sophisticated design that employs multiple microlenslet arrays and spot and pupil reimaging to overlap the beams from each group of these single-mode diode lasers into one spot to gain optical power and redundancy of emitters for reliability. This print-head, which was developed by Eastman Kodak Company, has been used in dry image setting systems by both Matsushita and Dainippon Screen.

#### 3.6.1 OPTICAL CONFIGURATION OF A MONOLITHIC MULTICHANNEL PRINT-HEAD

The key attribute of the monolithic multichannel print-head is that it uses a directly addressable laser diode array, provided with laser subarrays, which allows the system to provide source redundancy without resorting to an external modulator array.

![Diagram of anamorphic monolithic array and cross-array lens](image_url)
The optical layout, shown in Figure 3.25 for the along-array direction and in Figure 3.26 for the cross-array direction, employs an array direction intermediate imaging concept in which the respective beams from each of the addressed subarrays are collected into a printing beam, and the ensemble of printing beams are imaged to the media.

The laser diode array that powers this system comprises 160 single-mode, 835 nm diode lasers gathered into 10 groups or subarrays, which are separated by 250 µm spacings. Each channel, which is composed of 16 single-mode diode lasers spaced at 50 µm intervals, is 750 µm wide and driven by its own current driver. The total length of all of the single-mode diode lasers in the array is ~10 mm. As the fill factor of the laser array is very low (~6%), the challenge of optical system design is to increase the fill factor to nearly 100% on the medium without losing much optical power, while introducing a reasonable optical system complexity. Another requirement is that all 16 single-mode lasers overlap at the printing spot of their channel. Because the 16 single-mode lasers within a channel are mutually incoherent, each channel behaves optically like a multimode laser.

In addition to optical power gain for each channel, overlapping of the 16 single-mode diode lasers increases reliability. If a single-mode diode laser degrades in power or ceases to emit, the others can compensate the power loss by slightly increasing their

FIGURE 3.25  Array direction optics of a laser printer with addressed laser emitter subarrays. (From U.S. Patent 5,619,245)

FIGURE 3.26  Cross-array direction optics of a laser printer with addressed laser emitter subarrays. (From U.S. Patent 5,619,245)
emitted power. The multichannel print-head system reliability and robustness are improved significantly as a result.

In the array direction, the print-head uses a series of refractive lenslet arrays and field (or combiner) lenses to collect and gather the channels of beams to the media. The array direction optical system employs a classical optical design approach of object-to-image conjugation, intertwined with pupil-to-pupil conjugation, to obtain the image without loss of brightness. In greater detail, each of the 16 laser emitters in a given laser subarray is collimated by a collimator lenslet. Only two of the 16 emitters in each channel are depicted in Figure 3.25 for clarity. A second lenslet array (the combiner lenslet array) is provided with one combiner lenslet per laser subarray. The combiner lenslets focus the respective collimated beams from a given laser subarray in overlapping fashion, such that 10 separated beams (channels) are available downstream as imaged laser spots, which are presented nominally telecentrically to an intermediate image plane. The combination of a combiner lenslet with a focal length of 50 mm, and a collimator lenslet, with a focal length of 200 µm, is to magnify a ~4-µm-wide emitter by ~250 times to an ~1-mm-wide image (laser spot). Note that the 16 collimated beams are directed into the input aperture of the respective combiner lenslet such that, in total, the ensemble of 16 beams fills the aperture of the combiner lenslet and forms a combined Gaussian beam. As a result, although a given emitter has a miniscule NA (~0.1/250) at the imaged laser spots, the composite NA from the ensemble of 16 laser beams is a relatively large ~0.1.

The print media can be colocated at the image plane occupied by the imaged laser spots. However, both the spot size and the spot pitch may be incompatible with the printing specifications. Most simply, a printing lens could be provided to reimage the laser spots directly to the media plane to provide an array of addressed printing spots. A field lens near the intermediate image plane diverts the beams so that they pass through the aperture stop of the printing lens. If only this field lens is used, then a line of separated images of the beam combiner lenslets would be projected onto that stop, and a slight misplacement of that stop would severely vignette at least one of the outermost laser channels but not affect the central channels. This problem is remedied with the addition of another lenslet array, consisting of field lenslets. Each of these lenslets effectively reimages a corresponding combiner lenslet to the plane occupied by the aperture stop. In this context, the field lens causes each of the combiner lenslet’s images to be superimposed onto all of the others at the stop of the printing lens, equalizing the vignetting for all of the channels. As a result, the printing lens images the field lenslet array onto the medium and, as each field lenslet is nominally filled by the light of a given 1 mm laser spot, the optical fill factor at the media plane is high (~100%). The print lens reduces the spot size at a magnification of one-fortieth such that a row of 25 µm printing spots is presented telecentrically to the media.

The cross-array optics, shown in Figure 3.26, can be configured in numerous ways but, nominally, a variety of cylinder lenses is used to shape the beams. Gaussian beam waists are not formed to be coincident with the laser spot images, but to fall near the aperture stop of the printing lens, and at the media plane. The light from the single-mode diode lasers is first collected by the rod lens. The rod lens reduces the NA of each beam from the diode lasers in cross-array direction. The optical system
can form either a round spot or an elliptical spot, according to the relative magnifications in the array and cross-array directions. A two-cylinder lens system in the cross-array direction produces an elliptical spot with a 2:1 aspect ratio on the media, whereas a three-cylinder system produces a round spot.

After the fiber lens and combining lenslet array are aligned with the monolithic diode laser array inside the diode laser array enclosure, optical power vs. current is measured for each channel of an array both at the combining plane, 50 mm from the diode lasers, and at the focal plane intended to be coincident with the surface of the written medium. The typical efficiency of the optical system from diode laser to image-recording medium is approximately 70% for the print-head. Theoretical calculation suggests that the system optical efficiency should be about 80%–85%, implying that about 10% additional loss is observed. There are several unaccounted losses, such as excessive loss in the combining lenslet array, optical misalignment, and contamination of optical surfaces by dirt. This system can also be outfitted with a smile corrector, positioned between the combiner lenslet array and the laser spot images, to provide a dramatic increase in the effective depth of focus at the media plane.

3.7 LASER ARRAY AND MODULATOR ARRAY SYSTEMS

In recent decades, laser thermal print-heads with a large number of channels have been developed for various applications, including CTP plate setters for the graphic arts market. In general, the more channels in a print-head, the less laser power needed from each channel to maintain the same printer productivity, and thus the speed of the print-head relative to the medium can be slower. In the case of media mounted on a rotating drum, this means a lower r/min of the drum while exposing the media, and less time to accelerate and decelerate the drum to that lower r/min. In a flatbed plate setter, providing more channels in the print-head allows a lower print-head velocity while exposing the media, as well as less acceleration time, to reverse the print-head direction to that lower print-head velocity.

The preferred system architecture to achieve a large number of printing channels uses an integrated print-head wherein laser light illuminates a spatial light modulator array, which is subsequently imaged to the media plane. For example, this type of print-head can typically deliver 12–25 W of optical power to the media, compared to a total of about 10 W from the fiber optically coupled lasers and 6 W from the monolithic diode laser array. This design architecture also delivers the large number of high-power writing channels (e.g., 256 channels) more cost effectively than the system architectures discussed previously. As an additional advantage, the writing channels stitch seamlessly because they are derived from a continuous line of laser beam illumination. The design and performance of such systems is very dependent upon the properties of the spatial light modulator array.

This design space was first extensively developed by Xerox Corporation, which developed a complete solution including laser array sources, a viable modulator array technology, and the basic optical system configurations to transfer light from the laser array, through the modulator array, and to the media plane. Subsequent to these developments by Xerox, modulator array/laser array printing systems have been
developed by others, and used in products, including the Creo Trendsetter thermal plate setter\(^9\) and the KODAK NEWSETTER TH180 Platesetter System (developed by Kodak Polychrome Graphics\(^{TM}\)) for newspaper printing.\(^{10}\) These later systems were enabled by numerous technology improvements, in various areas, including for laser diode arrays, micro-optics, and spatial light modulator arrays.

### 3.7.1 The Xerox TIR Modulator Array System

An early printing system that combined a laser or laser diode array with a spatial light modulator array having a large number of channels (>5000) was developed by Xerox for electrostatic printing applications. This system is enabled by the total internal reflectance (TIR) modulator,\(^{87,88}\) shown in Figure 3.27, which comprised an adjacent row of pixels formed as individual patterns of electrodes on the top surface of an electro-optic substrate. The electrode patterns are formed as interlaced fingers to provide a structure of alternating polarity electrical fringe fields when voltage is applied. The electrical fields penetrate the electro-optical substrate, which is typically either lithium niobate (LiNbO\(_3\)) or lithium tantalate (LiTaO\(_3\)), to produce localized changes in the indices of refraction. Phase differences are imparted to the transiting light beam, which, in turn, result in diffraction patterns when the light is directed to a Fourier plane within the printing lens. The initial versions\(^{84,85}\) of the TIR modulator did not employ electrodes patterned directly on the electro-optic substrate, but rather a special multichannel silicon driver chip provided with electrodes that were proximity-coupled by contact with the electro-optic substrate. Although this approach provided an easy means for realizing a large number of pixels, the presence of an air gap between the electrodes and the substrate caused the required drive voltages to increase.

When proper spatial filtering is applied to discriminate between the light patterns of the modulated and unmodulated light, this Schlieren-type optical system provides the means to furnish an addressable array of pixels when the spatial light modulator array is imaged to the media plane. As the initial Xerox systems\(^{85,86}\) used coherent laser sources (HeNe lasers) and imaging of the light diffracted around the stop, the best results were obtained with Gaussian apodized stops (rather than square profile stops) as side lobe interactions were reduced. Although the TIR modulator is a transmissive device, which is generally advantageous, optimal operation of the modulator requires the light to attain grazing incidence in the region underneath the electrodes, which can be a significant impediment to the optomechanical system design.

![Figure 3.27: The linear TIR spatial light modulator.](image-url)
As shown in Figure 3.27, the input and exit faces can be cut at an angle,\(^{85}\) to enable an in-line optical system configuration.

The Xerox system,\(^{85,86,89}\) shown in Figure 3.28, introduces many of the basic elements required to optimize this type of printing system, including anamorphic laser beam shaping optics, *sheet or line* illumination to the modulator array, and imaging optics to couple light onto the print media. The unspecified laser source outputs a single beam, with a collimated meridian (aligned to the array direction of the modulator) and a divergent direction. The illumination system comprised an array direction beam expander, used to present collimated light to the modulator, and a three-element anamorphic cross-array optical system, used to focus the light to the modulator array. In the cases where a Gaussian beam laser source is used,\(^{86}\) the illumination system could be equipped with an apodizer, to uniformize the spatial light profile to within a few percent, but at the cost of a 50% light loss.

The printing lens comprised a field lens portion and an imaging lens portion. The central stop blocks the zero-order array direction diffracted light so that the higher-order diffracted light can be imaged to the media. As such, this system emphasizes modulation contrast over optical throughput.

As an alternative,\(^8\) Xerox also developed a system concept that uses a laser diode array as the light source where light from the multitude of laser emitters is used to flood-illuminate the modulator array. Laser coherence (or the lack thereof) contributes significantly to the actual performance of this type of system. In particular, the laser light must be sufficiently incoherent to avoid significant interference fringes. Accordingly, Xerox described a laser diode array comprising closely packed single-mode laser emitters, wherein the emitters are located in two parallel rows, with the emitters spaced at the same pitch, but 90° out of phase from one row to the other. As the resulting laser emitters are far enough apart to avoid phase locking, they lack a common phase and can be combined without interference. The beams were...
combined in the far field, without any uniformizing optics, to produce a generally Gaussian illumination distribution at the modulator array.

### 3.7.2 Spatial Light Modulators

This laser thermal printer design architecture, which combines a laser source (often a laser array) and a spatial light modulator array, would seem readily adapted to a wide variety of modulator technologies. In actuality, the applied power densities, geometry, and modulation speed requirements often limit the device technology choices, thereby eliminating LCD arrays and many micromechanical shutters from consideration. Moreover, the general linear arrangement of the system (including the laser diode array and the swath printing motion of the print-head relative to the media) favors a linear modulator array. Despite these limitations, several modulator array technologies have potential and have been applied in printing systems. Candidate device technologies include polarization modulators (such as PLZT), AOMs, digital mirror array modulators (DMDs), micromechanical grating modulators, and electro-optic grating modulators. Compared with many other applications that employ modulator arrays, the modulation contrast required to print on the typical graphics art media is quite low and is threshold rather than grayscale-based, such that a moderate (10–25:1) dynamic range is often sufficient.

The specifications on the spatial light modulator array can be considered more explicitly. The spatial light modulator array typically needs 200 or more independently addressable channels, and must be able to sustain a laser beam power density of about 1 kW/cm². This laser beam power density is rather high, and depends upon modulator pixel size, fill factor, and optical efficiency. The modulator must also provide a minimum contrast ratio of ~10:1 (the ratio of channel on irradiance to the channel off irradiance), and work well at semiconductor, diode laser bar source wavelengths, typically between 800 and 980 nm. In addition, modulated beam rise and fall times should be less than ~2 μsec.

From the optical designer’s perspective, the optimal modulator array would be a transmissive device, used at normal incidence, which either absorbs the incident light that is modulated to the off state or reflects it back toward the light source. However, most of the viable modulators are Schlieren-type devices, which impart phase modulation to the incident light, and require angular or Fourier plane filtering downstream. The quality of the modulation depends upon the angular filter design. The design of the angular filter in turn impacts the design of the printing lens, as access to an internal stop plane may be required, and also creates an inherent tradeoff between modulation contrast and system efficiency. In addition, the degree of partial coherence of the emitted laser light can affect the modulation performance of the Schlieren-type modulators. In lower power optical systems and applications, other modulator technologies, including absorptive devices, may also be viable.

Potentially, optimization of the modulator performance can also limit both the array and cross-array optical designs. For example, in the array direction, the length of the modulator array and the allowed NA for optimal response (modulation contrast, minimal crosstalk, etc.) may determine the array direction Lagrange supported by the system. Furthermore, to enhance the uniformity of the response across the
modulator array, the laser beam shaping optics may be required to present the modu-
lator with spatially uniform and telecentrically oriented incident light. Similarly, in
the cross-array direction, the modulator response characteristics and the pixel extent
may impose system constraints, including the amount of laser smile tolerated.

3.7.3 AN ARRAY PRINT-HEAD WITH A FLY’S EYE INTEGRATOR

In a printing system that employs a spatial light modulator array, the resulting print
quality is dependent upon the uniformity of response of both the modulator array
(pixel to pixel) and the illumination to the modulator array. Although a variety of
methods for improving illumination uniformity could be considered, including those
that use diffusers and integrating cavities, use of either light pipes (integrating bars)
or fly’s eye integrators is often appropriate in applications where it is necessary to
substantially preserve the brightness while providing uniform illumination. For
example, in the photolithographic printing of integrated circuits, a multitude of
designs have been used where the light from excimer lasers, YAG lasers, or arc
lamps has been made uniform by fly’s eye or light pipe integrators. These design
approaches are extendable into laser thermal printing, particularly in the instance
that a spatial light modulator array needs uniform illumination.

One exemplary laser thermal printing system that combines a laser diode
array light source, a spatial light modulator array, and light uniformization means is
shown in Figure 3.29. The print-head, developed by Eastman Kodak Company, com-
bines classical imaging optical techniques (object-to-image conjugation with pupil-
to-pupil conjugation) and traditional light integration illumination optics (the fly’s eye
integrator). In particular, the fly’s eye integrator, which is a portion of the array direc-
tional optical system of optics and micro-optics, contributes to flood illuminating a
spatial light modulator array with uniform light. In the cross-array direction, the light
from each emitter is focused to form a beam waist at the modulator, which is con-
fined within a narrow width corresponding to the defined active height of the modu-
lating pixels. In addition, the array and cross-array optics illuminate the modulator
array with a long, narrow line of light of uniform radiance, while largely preserving
the brightness of the laser diode array source (less transmission and other losses),

FIGURE 3.29 Laser printer using fly’s eye optical integration to illuminate a modulator
array. (From U.S. Patent 5,923,475.)
and providing redundancy relative to the emitters. The illuminated modulator is imaged telecentrically to the media plane by the print lens to create a line of closely packed writing spots. Depending upon the type of modulator array used, such as polarization type or a Schlieren type, the filtering means would be positioned in the vicinity of the printing lens, as appropriate.

As with many of the other laser thermal printing systems, the system of Figure 3.29 uses largely anamorphic (cylindrical) laser beam shaping optics, with separate optical systems designed for the array and cross-array directions. The operation of the array direction illumination optics (the laser lenslet array, the combiner field lens, several field lenses, and two uniformizer lenslets), as illustrated in Figures 3.29 and 3.30, is to collect light from each laser emitter, and magnify and redirect it such that the entire length of the modulator array is illuminated. In general, the fly’s eye integrator, which includes the two uniformizer lenslet arrays and the immediately adjacent field lenses, is designed to uniformly illuminate the modulator by dividing the light from each emitter into \( N^2 \) multiple beams. These \( N^2 \) beams are overlap imaged over the full length of the modulator array. For clarification, the image conjugate relationships in the system are shown as follows: planes \( a_0, a_1, \) and \( a_2 \) are conjugate to each other, as are planes \( b_0 \) and \( b_1 \). Plane \( a_0 \) corresponds to the front surface of the laser array, while plane \( b_0 \) corresponds to the back focal plane of the laser lenslet array. As a first stage of light integration, the laser lenslet array is used in combination with the combiner field lens to image the beams from each emitter in overlapping fashion to an intermediate illumination plane \( a_1 \). The laser lenslet array has \( N_1 \) lens elements, with each lens element corresponding to a given laser emitter. Although the light from the various emitters has been overlapped at the \( a_1 \) plane, the emitters have not been subsampled and mixed angularly or spatially. As a result, any systematic problems in the light profile across the emitters, such as the edge roll-off shown in Figure 3.6, are not removed, although such effects are averaged. Put another way, the light integration through the first stage is incomplete in that all points within the illuminated area do not see light from all points on each of the sources (emitters). However, if the near-field laser uniformity is improved consistently, the uniformization optics could be proven unnecessary.

![FIGURE 3.30 Light transfer within the fly’s eye integrator optical system.](image-url)
Thus, a second integration stage is used, which consists of the two uniformizer lenslet arrays and the adjacent field lenses. The preuniformizer field lens is used to create telecentric illumination at the intermediate plane $a_1$. The light profile at plane $a_1$, which is the magnified, overlapped, and averaged image of the emitters, is parsed into $N_2$ beams, where $N_2$ is the number of lenslets in the first uniformizer lenslet array. The corresponding $N_2$ lenslet elements in the second lenslet array work together with the postuniformizer field lens of Figure 3.29 to image the lenslets of the first uniformizer array in a magnified and overlapping fashion onto the $a_2$ plane (the modulator plane). The modulator plane field lens of Figure 3.29 functions in the same manner as does the preuniformizer field lens to provide telecentricity in the illumination. Thus, the intermediate $a_1$ illumination plane is subsampled by the $N_2$ uniformizer lenslet pairs to create a more uniform radiance distribution of light at the $a_2$ plane. The more $N_2$ lenslet pairs that are used in the fly’s eye integrator, the better the averaging. In general, the goal is to reduce the residual nonuniformity to just a few percent.

The laser beam shaping of this type of system can be further understood with reference to a specific laser diode array, such as the Opto Power OPC-A020 laser that was discussed previously. Again, the A020 array has 19 multimode laser emitters, each 150 µm wide, which are spaced apart on a 650 µm pitch, for an overall array length of 11.85 mm. In the array direction, the 830 nm light is emitted into a relatively small NA (~0.13), with a non-Gaussian angular beam profile and a relatively flat topped, but noisy, spatial profile (see Figure 3.6). The light emitted in the cross-array direction is output as a quickly divergent Gaussian single-mode beam (NA ~ 0.63).

In a first-order design, using the OPC-A020 laser, the refractive laser lenslet array (2.47 mm EFL) is designed to collimate light from the full field of each of the emitters. The laser lenslet array reduces the array direction Lagrange by effectively removing the spaces between emitters (~0.187 vs. 0.77 mm, otherwise). The focal length of the first field lens was chosen to overlap the $N_1$ beams at the $a_1$ intermediate image plane with the illuminated width bound by the constraints of the uniformizer lenslet array manufacture. Unless these constraints (size limitations on lenslet width, size limitations on the overall size of the array, or limitations on the sag height of the power surfaces) effectively limit the system, the design will be set up on the basis of convenience and conservation of brightness.

The fly’s eye assembly further directed the light to a modulator array, which, in this first-order design example, comprises 256 pixels, each 63.5 µm wide, for an overall device length of 16.25 mm. The design NA at the modulator plane is 0.023, which would be acceptable for most candidate modulator technologies. The uniformizer lenslet arrays, which were identical, each comprised six cylindrical lenslets, each 1 mm wide. The combiner field lens had a nominal focal length of 99 mm, such that the 6 mm overall width of the first uniformizer lenslet array is filled with light. The lenslet elements of the uniformizer lenslet arrays had 8.0 mm focal lengths to ensure that the output faces of the lenslets at the $b_1$ plane were filled with light. The 130 mm postuniformizer field lens provided the appropriate magnification to illuminate the full length of the modulator array. The print lens demagnified the modulator array at 1/6 times to provide a 2.7-mm-wide line of printing spots with an array direction NA of ~0.14.
Figure 3.31 illustrates the array direction illumination quality observed at the modulator plane with a prototype system based on the above design. The system yielded $\pm 6\%$ uniformity within the nominally uniform area created by the fly’s eye integrator, although better results are achievable. System light efficiency in the main beam at the modulator plane is $\sim 69\%$, with minimal light lost to the side lobes.

The cross-array optics of this exemplary system included a rod lens that is mounted to the diode laser assembly and a set of cylindrical lenses to provide a Gaussian beam waist at the modulator array, such that the light fits within the pixel height. Smile correction is used to effectively reduce the laser smile from $\sim 10$ to $\sim 2 \mu m$ residual. The illustrated system shows the printing optics as spherical, but anamorphic printing optics can be used if necessary.

During the system design process, detailed analysis and optimization using lens design software (such as ZEMAX or Code V) or illumination design software (such as Light Tools) or both, can be used to control lens aberrations and verify system performance. In addition, the first-order design can also be modified to help system efficiency. For example, an underfill factor can be applied during the layout of the uniformizer lenslet arrays so that the second array is slightly underfilled to compensate for broadening of the beams at the $b_1$ plane induced by both lens aberration and aperture diffraction. There is an opportunity, particularly with refractive lenslets, to experience light loss from scatter and diffraction at the seams where adjacent lenslets meet. Likewise, an overfill factor can be allowed at the modulator plane to allow for edge broadening at either end of the modulator. A similar system$^{11}$ can also be designed in which the far-field light profile, rather than the near-field light profile, is input into the fly’s eye integrator for light uniformization to then provide illumination to the modulator array. The difference can be regarded as providing a Koehler illumination input, rather than a critical illumination type input.$^{69}$
3.7.4 **An Array Print-Head with an Integrating Bar Homogenizer**

A variety of other laser thermal printing systems have been designed with other approaches to light homogenization, as well as other important features. As one example, a laser thermal printing system developed by Kodak Polychrome Graphics provided array direction light homogenization with an integrating bar\textsuperscript{10,21} instead of a fly’s eye integrator. Integrating bars or light pipes, which have also been widely used in projection systems, operate by a process of internal reflections to overlap and homogenize the light traversing their length. These bars are generally solid dielectric rectangular structures with the input and output faces at the opposing ends. Light propagates along their length and totally internally reflects (TIR) when it encounters the glass-to-air interface on the sides. The degree of uniformization is largely dependent upon the length of the integrating bar and the NA of the input beam. If the input light fills the input face, then light uniformization can occur without any significant loss of source brightness. In the case of the laser printer, the system is configured as shown in Figure 3.32 to provide numerous reflections in the array direction, such that the array direction light is made uniform. The exit face is then array direction imaged to the modulator plane. Conversely, the cross-array direction light underfills the integrating bar and propagates at a low NA, such that it sees the integrating bar as a thick window, and not as a uniformizer. As in many of the other systems, this printer can also use an array direction laser lenslet array (not shown in Figure 3.32) to reduce the effective Lagrange.

As another example, an IR (850 nm) laser thermal printing system\textsuperscript{9} is provided with two mirrors that deflect and redirect the sloping portion of the emitter light profile from one side of the array beam to the other, thus adding a compensatory way to the roll-off on the other side. This design approach, developed by Daniel Gelbart of Creo Incorporated (shown in Figure 3.33), has a modified critical-type illumination system\textsuperscript{69} that potentially corrects the macrononuniformities (roll-off) in the array direction, but may have little benefit in smoothing out the micrononuniformities, and will also only work well when the light profile is generally symmetrical. This approach also reduces the system brightness because of the increased angular

---

**FIGURE 3.32** Laser printer illumination of a modulator array, by means of an integrating bar. (From U.S. Patent 6,137,631.\textsuperscript{21})
spread of the illumination to the modulator, but the optical system is likely tolerant in the array direction to such an increase. In the cross-array direction (not shown in Figure 3.33), the rod lens focuses the light to the modulator plane. The printing lens then relays the beam focus to the media plane. As shown, the modulator is a polarization-type device (a PLZT modulator), and the system is equipped with a polarization prism to distinguish between the modulated and unmodulated light.

This system also uses the potential simplification of combining the laser lenslet array and combiner field lens (see Figure 3.33) into a single element. To begin with, the laser lenslet array is located at a working distance greater than the lens element focal length so that the emitters are imaged and magnified at the modulator plane. In addition, the pitch of the laser lenslet array is slightly smaller than the emitter pitch (the scale of Figure 3.33 obscures this detail) on the laser array (776.3 vs. 787.5 µm, for example), such that the lenslets are used as off-axis imagers, relative to the optical axis of the system. This off-axis imaging causes the magnified images to shift inward, such that the magnified images overlap at the modulator plane. Similar results can also be achieved by fabricating the lenslets on the same pitch as the laser emitters but with the optical axis of the lenslets shifted appropriately. The lenslet arrays used in this type of laser thermal printer, and several of the others previously described, can be designed and fabricated with diffractive (or binary) optical methods. The lenslet arrays can also have more complex designs, including aspherical power.

Certainly, the use of light pipes (straight or tapered, made of glass bars or mirrors) in light valve illumination systems can produce highly uniform illumination, at least with respect to low-spatial frequency variations across the field. However, as shown in Figure 3.34, high-spatial frequency nonuniform features, which are caused by residual interference effects, can occur. These interference effects are present even in systems with multiple quasi-monochromatic and mutually incoherent sources. The light pipe forms at its exit multiple virtual images, each one presenting a different reflection of the source at its entrance. These virtual sources are mutually coherent and will form an interference pattern even if the main source has very low coherence length. Figure 3.34 presents results of irradiance profile measurement at the light...
Laser Beam Shaping Applications

A measured irradiance profile at the light pipe exit, when illuminated with an array of mutually incoherent emitters. (Courtesy of Kodak Canada ULC, Burnaby, BC.)

Pipe exit illuminated with an array of mutually incoherent emitters. The sharp spikes and dips can be clearly seen on the top of the otherwise exceptionally flat profile.

Although most laser thermal print media are too insensitive to see such high-frequency spatial nonuniformities, these effects can cause problems for other processes. As a corrective measure\(^{105}\), a coherent nonuniform beam can be transformed into a noncoherent uniform beam using a light pipe whose aspect ratio is chosen so that the path lengths of the rays from the apparent sources to the exit of the light pipe are sufficiently different and greater than the coherence length of the laser light. In addition, a multiregion retardation plate is placed at the entrance of the light pipe to reduce the coherence length of the laser light. The minimum required light pipe aspect ratio (length divided by width) depends upon the input beam divergence angle \(\theta\):

\[
R_{\text{min}} = \cot \theta \quad (3.8)
\]

For a chosen aspect ratio \(R\) (preferably \(\geq 1.5–2x\ R_{\text{min}}\)) and laser coherence length \(C_L\), the minimum width of the light pipe can be calculated from the Equation (3.1):

\[
W_{\text{min}} = C_L \left( R + \sqrt{1 + R^2} \right) > 2R C_L \quad (3.9)
\]

Figure 3.35 illustrates a similar solution\(^{106}\), in which a random phase mask is positioned between the fast axis collimated laser diode bar and the light pipe entrance aperture. The phase mask provides areas with different thicknesses, and rays from the same emitter will pass through different portions of the phase mask and will acquire small phase retardation differences, preferably about half wave. As phase is then scrambled, coherence or interference effects are reduced. Alternate methods to reduce the spatial coherence of laser arrays while using diffusers in combination with light pipes are also known\(^{107}\).

In addition to providing redundancy and increasing available output power, increasing the number of laser emitters can also help to reduce the apparent level of
interference effects by averaging light from more independent sources. Notably, off-the-shelf laser diode bars typically have 10–19 emitters for 30% fill factor bars and 40+ emitters for 50% fill factor bars. Unfortunately, increasing the fill factor much further reduces the individual emitter brightness, thus reducing the gains.

Alternatively, light from multiple laser devices can be combined down a common illumination optical path. For example, wavelength multiplexing with dichroic combiners can be employed, but the laser bandwidth increase (e.g., wavelengths $\lambda_1$, $\lambda_2$, $\lambda_3$… as 810 nm, 825 nm, and 850 nm, respectively) can make the downstream imaging optics much more difficult. Polarization multiplexing, in which a half-wave plate
rotates the polarization of light from one laser device and a polarization combiner redirects that light onto the optical axis of the other laser, can also be used. However, this method of combining lasers is not suitable for systems that use polarization-dependent modulators such as the Xerox TIR modulator of Figure 3.27.

Therefore, it is more common in these systems to combine light from multiple lasers in angle space.\textsuperscript{108–110} Light can be combined in either the array or cross-array directions, but the latter can require that smile be well controlled or corrected, so there is sufficient Lagrange available. In either case, laser arrays can be placed in parallel along the long axis, and the emitted light from at least one laser device can be deflected into the common optical path.\textsuperscript{108,109} As shown in Figure 3.35, light from two collimated laser bars\textsuperscript{110} is directed by means of two folding mirrors to the entrance aperture of a tapered light pipe. Array direction light from each of the two arrays is mixed, and the net Lagrange is nearly the sum of the beam products of the two bars. A minimum beam product value is achieved in case of straight light pipe, whereas, in the fast axis direction, the beam product is essentially unchanged.

As each laser diode bar independently provides an incident line of illumination light to the spatial light modulator, care is required to ensure that these multiple lines coincide at the center of the modulator. Thus, as shown in Figure 3.35, a sampling mirror directs a small part of the power to a quadrant detector. The signal from the detector is then used by a servo system to adjust the two folding mirrors to precisely overlap the two illumination lines.

3.7.5 \textbf{Alternate Array Print-Head Designs}

Modulator array-type printers\textsuperscript{12,111} have also been explicitly developed for use with the grating light valve (GLV) modulator.\textsuperscript{93,94} In one exemplary system,\textsuperscript{12} developed by Agfa Corporation, the illumination beam is focused onto the modulator array, and the zero-order diffracted light is imaged to the media plane. An illumination system,\textsuperscript{112} shown in Figure 3.31, and designed in conjunction with this system, provides an array direction (slow axis) cylindrical lenslet array pair, comprising a collimating lens and an imaging lens for each emitter. This system magnifies each emitter to create nonoverlapped magnified images of the multimode near-field laser profiles, such that these images nearly touch, thereby providing a high fill factor line of illumination. This slow axis light propagates forward and encounters the cylindrical combiner collimator lens, which provides far-field images of each emitter in overlapping fashion as illumination to the modulator array.

In the fast axis (cross-emitter) direction, the rod lens collimates the beam and the array direction optical elements are regarded as windows. The fast axis narrowing lens then makes the beam slowly convergent. The cross-array beams are subsequently intercepted before the modulator array by a third cross-array cylinder lens, such that a collimated cross-array far-field \textit{image} is presented to the modulator array.

This system is somewhat similar to the fly’s eye-based illumination system\textsuperscript{11,102} presented previously, although that system reimaged and homogenized the near-field light profiles, rather than the far-field light profiles. However, the system of Figure 3.36 does not actually provide the means to correct a systematic repeating variation in the far-field spatial light profile from emitter to emitter, if such a
Laser Beam Shaping in Array-Type Laser Printing Systems

109

pattern should occur (see Figure 3.7). Effectively, this system provides Koehler-like illumination in the array and cross-array directions to the modulator.

In general, the modulator-array-type systems will benefit by the use of smile correction optics, 61–64 so that the cross-array beams can be combined with minimal Lagrange growth. Alternately, a cross-array optical design was proposed 44 that does not require additional optics or mechanics, in which aberrations are deliberately introduced into the cross-array optics as a means of smile correction. However, as the cross-array beam is broadened, the source radiance is effectively reduced.

The applicability of the modulator-type laser thermal printing system can potentially be further extended by combining the light from multiple diode laser arrays, 5,56,108 in order to hit higher power levels at the media. In addition, there are other system concepts in which a modulator array is illuminated by a laser but without consideration for source redundancy. In one instance, 20 a single high-power laser beam, such as from an argon laser, is split into a multitude of beams by a pair of beam splitters to illuminate a pair of AOM-type modulator arrays, such that each modulator pixel receives an individual beam. While this system is susceptible to the failure of the laser source, the beam splitting arrangement does provide the means to illuminate each modulator pixel identically. In another exemplary system, 113 an AOM array can be flood-illuminated by one or two laser sources, which may be either single-mode or multimode laser sources. Although the two-laser case (which combines beams by means of a polarization beam splitter) may provide a minimum of source redundancy, the design lacks provisions to uniformly illuminate the modulator array.

3.8 THERMAL EFFECTS IN OPTICS

These laser printing systems have been discussed relative to enabling processing of printing plates by thermal ablation. In higher energy systems, such as IR laser systems used for laser cutting and laser welding, and pulsed systems, energy densities can be high enough to cause significant thermal problems in the optics themselves.
Although the energy levels are not high enough to cause laser-induced damage (e.g., compaction or cracking), both thermal defocus and thermally induced stress birefringence can cause significant problems at these light levels used in laser thermal printing.

### 3.8.1 Thermal Defocus

In general, optical design approaches for reducing laser-induced thermal defocus have emerged from the laser materials processing field, where lasers are used to cut, drill, and weld metals and other materials. In laser systems, thermal defocus generally occurs with \( \frac{dn}{dT} \), the change of refractive index with temperature, although thermal soak temperature increases and thermal gradients can cause different effects. These sensitivities can be described by two terms, each of which depend upon \( \frac{dn}{dT} \): the thermal glass constant (\( \gamma \)), which represents the thermal power change that is due to an optical material, and the thermo-optic constant (\( G \)), which accounts for the thermal response of an optical material to radial gradients. In one example, using thermal glass constant (\( \gamma \)), an IR laser system is described in which light from a 20 kW fiber laser is to be imaged to a material, and three simultaneous equations are solved to achromatize and athermalize the lens so as to maintain focus over a wide temperature range.

Although the laser printing systems typically operate at appreciably lower power levels than those in 1–20 kW laser thermal processing systems, a mere 80 W of CW optical flux can cause significant thermal defocus if the laser wavelength is even only moderately close to absorption peaks of one or more of the optical materials used (e.g., absorption coefficient \( \alpha \approx 0.001 \text{ mm}^{-1} \)) in the lens. Depending upon the system design, and depth of focus or Rayleigh range thereof, the resulting focus shifts may or may not be significant. Although use of autofocus may resolve any problems that occur, it still can be valuable to design the optics to reduce these effects. In addition to applying a design approach that reduces thermal defocus, careful glass selection can be key. Such efforts can emphasize using glasses with low-absorption (e.g., fused silica) or near-zero thermal gradient sensitivity (e.g., calcium fluoride-variant glasses such as N-PK51A). It can also be valuable to select glasses for one or more elements in a multielement lens that have a negative gradient \( \frac{dn}{dT} \) value, while the other elements have a positive \( \frac{dn}{dT} \) value, so that \( \frac{dn}{dT} \) values compensate. Notably, calcium fluoride and other fluoride glasses (e.g., BaF\(_2\) and LiF\(_2\)) satisfy the first requirement by having negative \( \frac{dn}{dT} \) values. However, it should be noted that many of these materials, including crystalline materials such as CaF\(_2\), are susceptible to thermal shock and fracturing, so care is required in their use.

### 3.9 Opportunities and Conclusions

Since the late 1980s, environmental concerns have demanded new printing technology that is environmentally conscious and dry, free from any wet chemical processing. Laser thermal printing meets this requirement while it provides the same image quality as silver halide in terms of resolution and density for reflective and transparent...
images as well as printing plates. Laser thermal’s requirement for more laser energy
than silver halide can be satisfied by several multichannel print-head architectures.

The laser thermal print-heads that were developed to meet these needs span
a range of viable optical design architectures, including the direct laser to media
systems, optical fiber-based systems, the modulated subarray laser approach, and
the spatial light modulator array-based systems. A range of enabling technologies,
including micro-optics, high-power laser diode arrays, spatial light modulator arrays,
and new optical media, have helped to make these systems possible. The associated
laser beam shaping designs, while generally evolutionary, have employed the lasers,
micro-optics, and other components, in complex and elegant designs that combine
classical imaging and Gaussian beam optics into unitary systems. Furthermore, many
of these systems, and the designs that enabled them, have been proven viable in the
market place.

Certainly, as new components emerge, there will be further opportunities to
design higher performing and lower cost systems. For example, optically pumped
fiber lasers could be a useful high-power laser light source for these types of systems.
Moreover, there are market opportunities beyond laser thermal printing, such as
color laser image projection\textsuperscript{117–119} and the manufacture of organic LED devices,\textsuperscript{120}
which can potentially benefit the design approaches and solutions developed to sup-
port laser thermal printing.

REFERENCES

1. Leger, J. and Golstos, W., Geometrical transformation of linear diode-laser arrays for
longitudinal pumping of solid state lasers, \textit{IEEE J. Quant. Electron.}, 28(4), 1088–1100,
2. Goring, R., Schreiber, P., and Poßner, T., Microoptical beam transformation system for
high-power laser diode bars with efficient brightness conservation, \textit{SPIE Proc.}, 3008,
3. Fan, T., Sanchez-Rubio, A., Walpole, J., Williamson, R., McIngailis, I., Leger, J., and
4. Head, D. and Baer, T., Apparatus for coupling a multiple emitter laser diode to a multi-
6. Yip, K., Thermal dye transfer apparatus using semiconductor laser diode arrays, U.S.
8. Thornton, R., Incoherent, optically uncoupled laser arrays for electro-optic line modu-
9. Gelbart, D., Apparatus for imaging light from a laser diode onto a multi-channel linear
10. Sarraf, S., Light modulator with a laser or laser array for exposing image data, U.S.
Patent 5,521,748, 1996.
5,923,475, 1999.
12. Reznichenko, Y. and Kelley, H., Optical imaging head having a multiple writing beam
Laser Beam Shaping Applications

93. Hornbeck, L., Multi-level deformable mirror device with torsion hinges placed in a layer different from the torsion beam layer, U.S. Patent 5,600,383, 1997.