Optical Systems for Laser Thermal Printing

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ABSTRACT

This paper is an overview of the optical designs used in array-type multispot laser thermal printers. A variety of unique systems have been developed for high-power high-throughput printing applications where laser light is generally transformed into a linear arrangement of modulated beams focused onto light-sensitive media. The typical light source is a monolithic laser diode array that emits a series of anamorphic partially coherent infrared beams. An optical system, comprising anamorphic, micro-optics, and designed according to principles from classical imaging optics, illumination optics, and Gaussian beam optics, is needed to conduct the light to the media. Special optical components, including rod lenses, laser smile correctors, or spatial light modulator arrays may be employed. Because the printing applications are highly sensitive to repetitive artifacts, the designs typically provide light source redundancy and light homogenization. The interaction of the incident light with the thermal media can also affect the design. These various optical design issues, and a number of design solutions, are the subjects of this review paper.

Keywords: Laser thermal, laser printer, laser diode array, micro-optics, anamorphic optics, spatial light modulator

1. INTRODUCTION

There are many applications for an optical system that delivers a large number of independently modulated channels of focused high-power laser light. While some of these applications, such as laser based image projection and organic LED display patterning, are still emerging, various systems have already been developed for use in laser thermal printing. These systems, which have some affinity with longitudinal solid-state laser pumping[1] and fiber laser coupling optics, have used complex arrangements of laser sources, micro-optics, Gaussian beam shaping, and classical imaging and illumination optical design approaches. While this paper presents a more extensive survey of this field than has been provided elsewhere,[2,3] the material will be reviewed in greater depth in a pending book.[4]

The typical laser thermal printer is distinct from the traditional flying-spot laser printer. In a flying-spot laser printer,[5] 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, that is modulated to create the correct density of each spot, pixel by pixel. As the laser spot is swept in the line-scan (fast-scan) direction to produce a line of image data, the media is moved in the page-scan (slow-scan) direction to create a two-dimensional image. Although multispot flying-spot laser printers have been developed, the flying-spot configuration does not readily provide large numbers of individually modulated laser writing beams.

Compared to the flying spot laser printer that uses a single mode laser diode, laser thermal printers use high-power infrared laser diode arrays. As laser arrays can be designed in numerous ways, including with phase-coupled single-mode emitters, uncoupled single-mode emitters, or uncoupled multimode emitters, the output properties of the individual beams and the ensemble of beams vary dramatically. Many beam properties, including the output power level, beam profiles and beam propagation properties, beam coherence effects, and the overall device layout, are dependent on the emitter structure. The linear arrangements of the laser-array emitters, as well as the anamorphic light emission properties, help motivate anamorphic optical designs.

The typical laser thermal printer operates like a lathe, where the page-scan motion is obtained by rotating a drum (at speeds up to 3000–4000 RPM), which holds the media, and line-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, graphic arts laser thermal

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printers are available that simultaneously deliver high resolution (2400 dots/in. (dpi)) and high throughput (15 proofs/hr), while printing on insensitive threshold-effect media (0.2–0.5 joules cm^2).

Aside from providing the required optical power and power density in the requisite number of spots, laser thermal printers can be characterized by the choice of light modulation means and the extent to which redundancy has been designed into the system. Integral laser arrays can be used, with the laser emitters driven individually to provide writing beams, which are imaged directly at the media. While such systems are simple, and possess low unit cost and high light efficiency, this type of printer is susceptible to the failure in the array because a pattern error results. To address the redundancy issue, laser printers can be constructed in which individual laser emitters or groups of laser emitters are defined as a single writing channel, and multiple laser emitters (or multiple groups) are assembled to form a multichannel print-head. Exemplary systems have been constructed using free-space propagating beams, as well as optical fiber-coupled beams. In these cases, a failed laser diode source can be replaced and the redundancy requirement met, but the overall system complexity has increased significantly.

Alternately, a monolithic diode array source can be constructed using a series of subarray laser sources. Light from each of the lasing elements of a given subarray is combined into a beam, which is 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.

Printing systems have been also designed where 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. The modulator array is imaged to the media as an array of printing spots. The laser source is greatly simplified because it operates at full power without direct modulation, and flood illumination desensitizes the system to laser emitter failure. However, illumination nonuniformities can cause printing artifacts. Additionally, the modulator array must have the proper optical characteristics (modulation speed, contrast, optical fill factor, etc.) to be effective, while being sufficiently robust to operate in a high flux environment.

2. PRINT-HEAD/MEDIA INTERACTION

Laser thermal printing can be used to produce directly viewable images on paper or transparencies. A writing laser beam can interact with a medium to form an image in a variety of ways, including dye transfer or sublimation from a donor sheet, ablation of dye from a support, polymer crosslinking, and phase change.[6] For example, a laser thermal donor media suitable for continuous-tone applications can transfer 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 light absorption causes the donor to be heated to temperatures higher than the dye's vaporization temperature. The receiver can be offset from the donor layer by a layer of widely distributed matte beads.

In such media, layers of infrared and visible dyes are coated in a binder on the bottom surface of a donor sheet. As the incident laser beam is applied, light absorption in the dye causes heat to accumulate, with the fastest heating 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. The typical laser thermal dye-transfer medium is a threshold medium, meaning the dye is transferred only from regions that retain enough energy to reach a vapor phase.[7] 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; but some of the heat deposited by the leading half of the beam has diffused away, reducing the maximum temperature attained. It should be noted that there are types of laser thermal media, including media that operate by an "eruptive" process, in which an internal laser-heated layer expands abruptly through the over layers on a localized basis.

2.1. 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 image density. Depth of focus can be defined relative to the production of the highest uniform densities, rather than the more typical narrowest waist criteria. In effect, the depth of focus becomes the distance from best focus that causes the image density to drop a specific amount.[8]

Laser thermal printing can also benefit from nearest-neighbor thermal interaction effects.[6,9] Thermal interactions can occur between the temperature profiles produced in a donor by simultaneous exposure with multiple sources. In particular, simultaneously writing with multiple adjacent spots enables some spots to exploit the skirts of the neighboring spots' exposure distributions, thereby utilizing energy that would be squandered by writing with a single spot. Nearest-neighbor interactions that increase the output density occur when the optical writing spot is larger than the scan-line spacing. Alternately, it can be stated that the energy from a single laser is used less efficiently than the energy from two or more laser spots operating in proximity, in both space and time, when the optical writing spot is more than one raster line wide.

This nearest neighbor effect interacts with the optical design in interesting ways.[6] For example, 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 MTF and makes it more difficult to balance or adjust the swath response to hide the intensity and placement errors because interactions extend across several neighboring writing spots instead of only to the nearest-neighbor spots. The use of smaller writing spots increases MTF and makes nearest-neighbor effects more controllable but also reduces the effective depth of focus.

2.2. 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, laser thermal media crosstalk (the nearest-neighbor effect), or both. Thermal interactions produced in the donor (which are typically beneficial) are distinct from thermal crosstalk effects between emitters within an array (which are generally to be avoided). Use of the nearest-neighbor effect also requires the use of channel compensation and calibration methods,[9] so that instances when "single," "pair," and "triple" line patterns are printed, they result in similar densities to instances when the entire print-head is activated.

A significant efficiency advantage can be attributed to the high fill-factor multisource laser thermal print-head over the low fill-factor configurations.[6] 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 ~60–80% of the exposure required by a series of single-beam exposures to generate the same rise in dye-layer temperature. A high fill-factor print-head provides a line of writing spots that are immediately adjacent, or nearly so. By comparison, in a low fill-factor print-head, the writing spots or pixels may be spaced apart with a low fill factor or duty cycle (70% or less). 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.[10,11] 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 to address pixel structures on a finer pitch. However, tilting introduces time delays between leading and lagging writing spots, and therefore heat dissipation reduces the beneficial thermal crosstalk between adjacent spots.

2.3. Laser/media interaction – Spot size, shape, and profile

Because many graphics applications require high-resolution printing in the 2400–3000 dpi range, the writing spot (or pixel) may be as small as 8.5–10 μm in size, although larger spots (25–50 μm) are sufficient for some applications. In the array direction, the writing spot size is the system dpi specification, modified by other factors such as the light profile, nearest-neighbor, and media effects (dot gain, for example). 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 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 on the light profile within the writing spots. Many systems have configurations in which at least one axis (typically the fast-scan axis, which corresponds to cross-array or cross-emitter) presents a nominally Gaussian profile focused spot to the media. In the orthogonal (slow-scan or array) axis, the light profile at the media may also be Gaussian. However, there are systems that 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 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 uniform writing-spot profiles can be expected to experience reduced nearest-neighbor interactions, compared to the Gaussian writing spots.

The multimode lasing behavior intrinsic to many diode lasers can also affect the depth of focus and the energy profiles of the focused beams, resulting in image quality degradation. In particular, multiple modes within a converging light beam have a localized spatial coherence that can cause that light to focus differently from the main beam, producing hot spots with different best-focus positions and extents. If these hot spots persist sufficiently to modify the local temperature profiles, variable heating and thermal media responses can occur. 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, including the removal of higher-order time-variant modes[12] or optics that homogenize or diffuse the mode structure.

3. LASER SOURCE CHARACTERISTICS

Most laser thermal printers have used laser diode arrays, although a few have employed discrete laser diodes, either fiber coupled[13,14] or arranged into a multibeam print-head with secondary combining optics.[15] Diode laser arrays[16] have been designed and fabricated in great variety, including devices with 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 typically use high-power IR arrays, which are available over a relatively narrow spectral range (~800–980 nm).

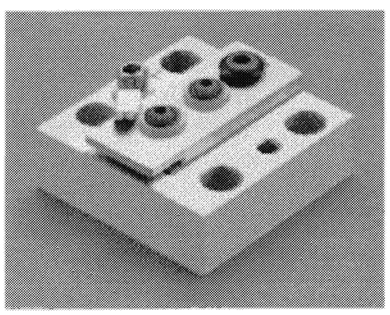

Fig. 1. A laser diode array package.

The typical high-power laser diode array package (see Fig. 1) 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.

In some designs, the lasers and laser arrays are operated as continuous-wave (CW) light sources that illuminate a separate modulator, thereby avoiding the complications of direct emitter addressability. Providing individually addressable emitters directly within a laser array is nontrivial, 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 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).

3.1. Laser coherence and beam shape issues

Generally, the laser sources used in laser thermal printers are only modestly coherent. As an example, an OptoPower 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, while still minimizing thermal crosstalk effects between emitters. In the array direction, the light is emitted into a small numerical aperture (NA ~ 0.13 for the A-020 laser) but with a very non-Gaussian angular beam profile. As these lasers have a large emission bandwidth ($\Delta\lambda$) of ~3–4 nm for a laser, the output light is nearly incoherent temporally, with a short coherence length $C_L = \lambda^2 / \Delta\lambda = 0.2$ mm.[17] Approximating the array direction beam as an incoherent uniform source, the coherence width (or coherence interval) C_I [$C_I = (2*0.16*\lambda)/NA = 2$ μm] of these lasers is small, compared to the 150 μm array direction emitter width.[18]

Assuming that such multimode lasers are largely free of filamentation effects, the array-direction emitted light is spatially incoherent across each emitter. As a result, the array-direction near-field light profile across the emitters can be flat topped with minimal rippling from intra-emitter interference. Figure 2 shows an exemplary profile, with a general rolloff overlaid with some rippling effects, for a combination of both macro- and micro- spatial non-uniformities. Thus, in the array direction, the emitters approximate miniature incoherent or partially coherent extended sources. Furthermore, as the emitters are generally not phase coupled with one another, the light from the various emitters can be superimposed at the modulator without incurring interference effects.

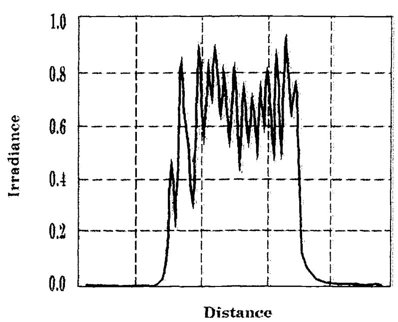

Fig. 2. Near-field beam profile for a multimode emitter.

Figure 3 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 ~ 0.07–0.14) and the cutoff is sharp, the profile is not uniform but is often bimodal, with a pronounced dip in the center.

This double-lobed structure is evidence of some near-field filamentation within the laser. The filamentation has a dominant spatial frequency that depends on how hard it 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.[19]

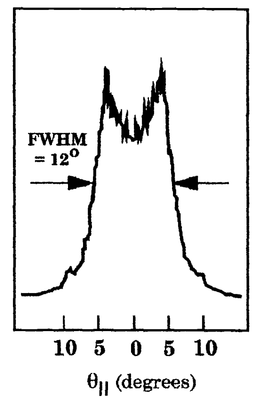

Fig. 3. Far-field energy distribution of a multimode emitter.

By comparison, the light emitted in the cross-emitter direction is a nominally single-mode (TE_{00}) beam with near-field and far-field Gaussian beam profiles. The light emitted in the cross-array direction is output out over a much larger numerical aperture (NA ~ 0.63), corresponding to a cross-array direction Gaussian beam $1/e^2$ emitting width of $H = 2*\lambda / (\pi*NA) = 0.85$ μm. 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 cross-array direction light (laser fast-axis direction) is coherent over the beam width (approximated by the $1/e^2$ emitting width). Although each laser emitter outputs a coherent cross-array direction beam, individual emitters can be phase de-coupled from each other, and thus the beams can be combined without cross-array interference.

3.2. Laser arrays as light sources

Light sources are defined not only by their coherence but also by their optical extent, which is classically referred to as the etendue or the Lagrange. In particular, 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 integrated over the entire source. In most optical systems, it is desirable that the etendue or Lagrange be conserved throughout an optical system, in order to maximize light efficiency and conserve radiance.[20]

Laser diode arrays are atypical light sources because they have dramatically different Lagrange values in the two meridians. In the array direction, where the typical laser array emitter is an incoherent or partially coherent source, the emitter Lagrange can be estimated as $L = NA*w/2$ (numerical aperture × half width). In the cross-array direction, each emitter is a coherent single-mode (TE_{00}) Gaussian beam light source, and the Lagrange can be estimated as $L = \omega*NA = \lambda/\pi$.[21] These widths are usually estimated at the half maximum or ~10% intensity levels.

For a high-power laser diode array, as depicted in Fig. 4, the emitters are multimode in the array direction and single mode in the cross-array direction. 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 corresponds to the cross-junction direction for which the emitted beam is generally Gaussian, with relatively poor beam quality, and has a large angular divergence ($\theta_{\perp}$).

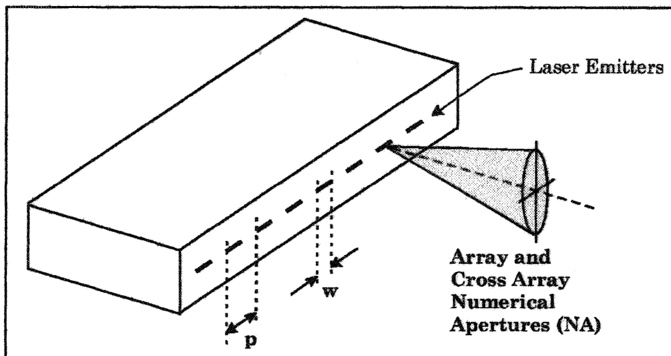

Fig. 4. Emitting geometry of a linear laser diode array.

The exemplary OPC-A020 laser array has an array-direction emitting width (w) of 150 μm, and an array direction NA of ~0.13, for an emitter Lagrange of L = NA*w/2 ~9.75 μm. The array direction Lagrange for the entire laser array (19 emitters) is therefore ~187 μm, assuming that the array-direction optics are designed not to see the non-emitting spaces (p – w) between the emitters. The space between emitters can be optically removed by collecting light with an array direction-oriented lenslet array. If, conversely, the light were collected with a single lens, the array-direction laser Lagrange would be fairly large (L = 0.13* 11.85 mm / 2 = 0.77 mm). This difference in the collected Lagrange can impact the angular width (numerical aperture (NA)) and optical efficiency throughout a system.

In principle, the cross-array direction Lagrange is equivalent to the Lagrange of a single-laser emitter, which as a single TE_{00} mode Gaussian source, is estimated as $L = \lambda/\pi$. Thus, an 830 nm laser will have a cross-array Lagrange of ~0.26 μm emitted into a highly divergent beam (NA ~0.5–0.6). The typical single mode-by-multimode laser diode array then has array and cross-array Lagrange values that differ by ~700X.

The entire ensemble of differences in beam emission properties (mode structure, relative coherence, output numerical aperture, and brightness or Lagrange) help to motivate the very different array and cross-array laser beam-shaping optical designs used in many laser thermal printing systems. In general, the cross-array optics are designed according to Gaussian beam propagation principles, while the array direction optics, which receive generally incoherent light, are designed according to classical imaging optics and illumination optics design principles. Therefore, most such optical systems employ numerous cylindrical elements, so that the light beams can be shaped and directed independently.

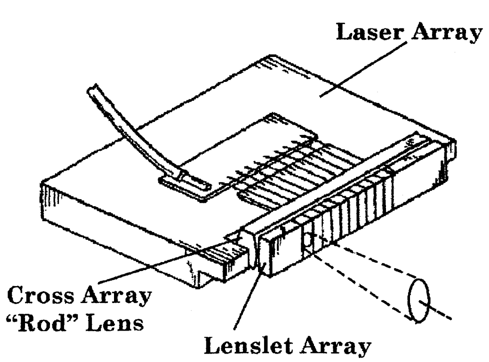

Fig. 5. Laser diode array package with integrated cross-array and array optics. U.S. Patent 5,212,707.

4. CROSS-ARRAY OPTICS

In the cross-array direction, the typical design intent is to collect the light into a beam that is transmitted through the array-direction optics with minimal crosstalk effects, and focused onto the media plane. Typically, the printing application defines the desired spot size (the "dpi" required) with the numerical aperture determined by the depth of focus required by the media handling system. In the case that an external light modulator is used, there may be further cross-array beam size and numerical aperture constraints imposed on the design.

The cross-array optics, which are only shown in the most basic way in Fig. 5, typically include a "rod lens" and one or more cross-array lenses. The lenslet array can have optical power in the array direction, cross-array direction, or both. But commonly, the array is anamorphic and operates on the array direction light. The rod lenses are microlenses with very short focal lengths (~100–200 μm), which enable spherical aberration to be minimized, enhanced by special corrections designed into the lenses. For example, the rod lens 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.[22] These lenses are typically used to collimate the cross-array light, although they can be used to reduce the laser divergence to a lesser extent (to less then full collimation). The use of a rod lens also allows the high numerical aperture cross-array light beams to be controlled before the light beams become awkwardly large.

4.1. Laser smile error

While the cross-array laser beam-shaping optics can comprise a simple arrangement of cylindrical lenses, laser-array "smile" (see Fig. 6) provides an added complication. Although the laser emitters have nominally identical emissive properties, including an emitter Lagrange of λ/π, they may not be located in a perfect linear arrangement. In Fig. 6, which is a near-field projected image, the laser emitters can be pattern offset with a slowly varying error spanning a few microns. The net effect of this diode-laser fabrication error is that not all the laser emitters on the same substrate emit beams from the same plane.

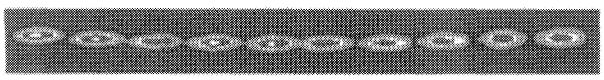

Fig. 6. A line of printing spots exhibiting laser smile error.

An uncorrected smile error can manifest itself as a printing artifact or inefficiency, potentially creating directly viewable artifacts. Most directly, the smile pattern can be projected onto the medium as an arch (or "arc") in the sequence of writing spots. A smile error can also create banding when a tilted print-head is used, as the distance or pitch between emitters (writing spots) is no longer constant. In systems using flood illumination of a modulator array, the emitted beams are intermingled, and 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 10X, or more, from the Gaussian λ/π, with a resulting impact on efficiency, printing artifacts, and spot formation at the media (depth of focus, spot size).

Although laser array manufacturers have improved their ability to control or minimize smile error, numerous means[23-25] for smile correction have been developed. Assuming the laser arrays have smile errors that follow a simple "s" or "c" shaped arc, smile error can be compensated for by bending the rod lens to a matching arc.[22,24] The resulting line of collimated laser beams are traveling in parallel to the optical axis but with slight offsets. Smile correction at or near the rod lens is preferable, as the beam deviations may no longer be separable once the beams have been intermingled.

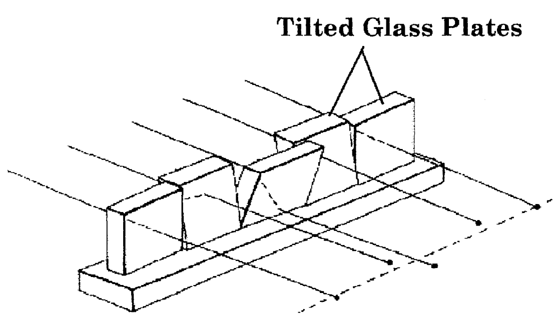

Fig. 7. Laser smile correction using an array of tilted plates. U.S. Patent 5,854,651.

Smile correctors have also been developed that can correct laser-array smile without benefiting from a dependence on the shape of the smile error. One such smile corrector,[23] shown in Fig. 7, 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. Smile correction has also been provided with individual cross-array lenses or mirrors adjusted on a per-emitter basis or by using optical aberrations to broaden the apparent cross-array emitter size.

5. DIRECT LASER TO MEDIA SYSTEMS

As a design architecture for a multichannel laser thermal printer, the configurations in which a series of discrete laser sources directly provide a series of laser printing spots are 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 directly mapped to the media. Alternately, the laser beams can be routed to the media indirectly by means of optical fibers. The laser sources can also use individual external modulation devices. However in general, this type of system has significant vulnerability to the degradation of individual laser sources, although field replacement can mitigate this weakness.

5.1. Laser emitters mapped to the media

Aside from a "contact" printing approach, the simplest architecture is to image an array of directly addressable laser diode emitters to the media plane. In one system[26] developed by Eastman Kodak Company and shown in Fig. 8, a linear array of individually addressable laser diodes is monolithically integrated on a semiconductor substrate. The system uses spherical optics to image the laser array directly onto the media, so each laser diode corresponds to a pixel in a line on the print. While a variable response from laser emitter to laser emitter across the laser array can potentially be corrected via a calibration process, any outright emitter failures would provide uncorrectable line artifacts.

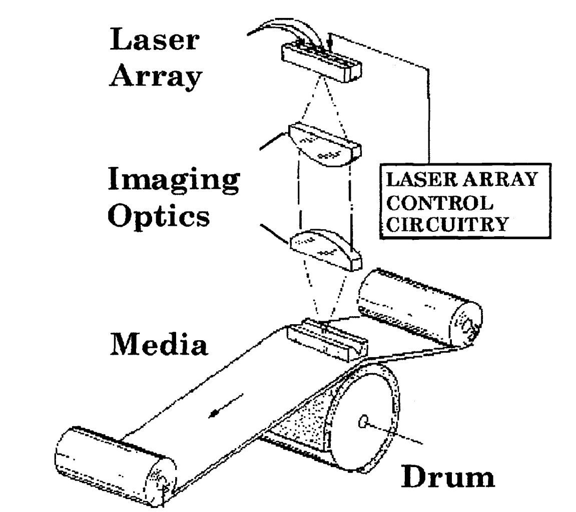

Fig. 8. Printer configuration with an addressed laser array imaged directly to the media. U.S. Patent 4,804,975.

There are several variations to the basic direct-array imaging system of Fig. 8 that have been proposed or demonstrated. The laser array can comprise single-mode emitters, or alternately, a series of single mode-by-multimode emitters. The systems are typically anamorphic, using a cylindrical rod lens and a spherical printing lens, providing a row of nominally circular printing spots. The printing lens can be double telecentric (telecentric in both object and image planes), so that the printing spots have a common depth of focus across the drum.

As an alternate approach,[27] the system shown in Fig. 9, uses a nonaddressable laser-diode array with the emitted light 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 with each emitter illuminating 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 beams directly to the modulator array. The modulator array is, in turn, imaged to the media by a printing lens (not shown).

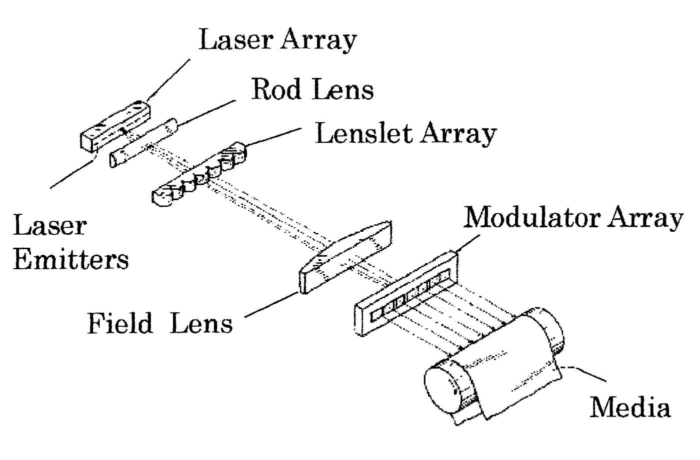

Fig. 9. A system with the emitters mapped to provide adjacent non-overlapping illumination of a modulator array. U.S. Patent 6,356,380.

5.2. Multiple discrete lasers mapped via free-space optics

Although many laser thermal printer designs have used high-power laser arrays, either directly addressed or indirectly modulated, some systems have been developed that use a series of discrete laser diodes. As an example, the Polaroid Helios systems[15,28,29] use a design approach in which a series of free-space propagating beams are combined to form a print-head. Like 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 medical imaging market, the pixels were printed in grey scale (256 levels) modulation by writing each pixel with a "half-toning" process using a series of subpixels. The subpixel structure was written by a combination of four independently modulated laser diodes.

The basic Helios system[15,28] shown in Fig. 10, comprised four laser beams that were combined via a multifaceted mirror to subsequently follow parallel optical paths through the remaining optics (see Fig. 11). The mirror array provided two offset, opposing facets that redirected two of the laser beams into parallel paths. The third beam passed between a gap between the two opposing facets, while the fourth beam deflects off a tilted mirror located in the gap between the two opposing facets.

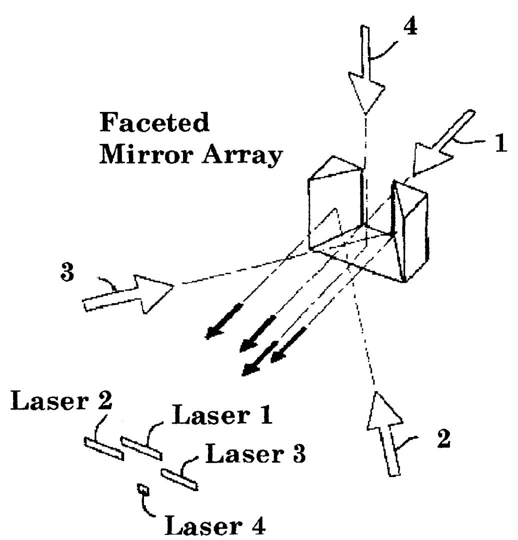

Fig. 10. Printer configuration with a laser array synthesized from free space lasers. U.S. Patent 5,161,064.

The Helios system provided a unique configuration of four printing spots, providing a subpixel structure to write 90 μm × 90 μm 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 was designed to have ~1/7th the energy of each of the other three beams so that accurate tone-scale reproduction could be provided for the highest density regions of the print. Although Fig. 10 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 compensates for irradiance variations from diffractive interactions at the mirror facet edges, thereby reducing printing artifacts.

The four laser-diode lasers are high power (500 mw) IR (820 nm) single-emitter lasers, with single mode (~1 μm wide, 1/e^2 NA ~ 0.5) by multi-mode (~100 μm, NA ~ 0.07) emission structures. The laser beam-shaping optical systems (see Fig. 11), which are largely identical for the four lasers, begin with a fast (NA ~ 0.55) molded glass aspheric spherical collimating lens. Ultimately, the desired subpixel structure at the media plane comprised three ~34 μm long × ~3 μm wide spots and a small spot of ~5 μm × 3 μm width. The focusing objective was a similar lens to the collimator and had a 0.47 NA and presented the printing beams telecentrically to the media plane. The telecentricity requirement was 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.

As the printing spots are formed by imaging the laser emitters onto the media plane, the optical system provides differential laser beam shaping, with the cross-array beam is magnified by ~3X, while the emitters are demagnified by ~3X in the multimode emission direction. It was also desired that the numerical apertures in the two meridians be nearly equal at the media plane. As a result, an ~8–9:1 anamorphism is required somewhere within the beam-shaping optics.

As shown in Fig. 11, 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, afocal beam expander. These illumination systems provide magnified intermediate real images of the laser emitters in both the multimode and single-mode directions. The illumination systems are arranged radially about the mirror array with the magnified real images of the laser emitters 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.

Before reaching the focusing lens, the four beams travel through a common anamorphic collimator, comprised of two crossed cylinder lenses, which is used to equalize the printing numerical apertures 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. 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,[30] with the source profiles ultimately imaged to the media, which makes the printing sensitive to the array direction near field-emitter light profiles. Polariod addressed this issue by developing laser diodes with more uniform laser-near-field profiles than were commercially available.[29]

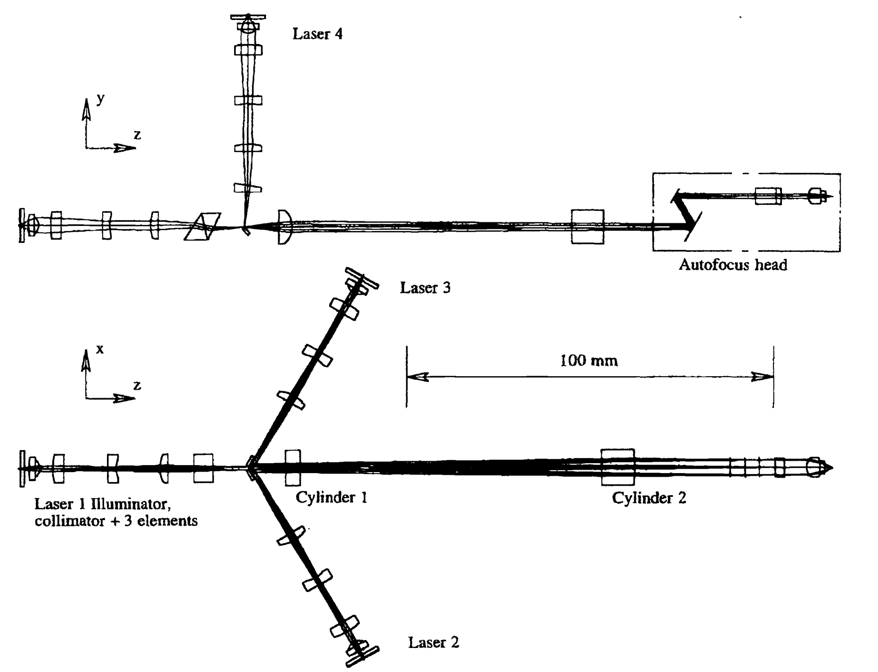

Figure 11. The Helios optical system from Polaroid, with four beams combined to form a printing spot with sub-pixel addressing. U.S. Patent 5,161,064.

While the illumination systems for lasers 1–4 are nominally identical, the illumination systems for lasers 1 and 4 are augmented with prismatic wedges. These wedges provide telecentricity correction, as well as coma correction, needed by the vertically offset laser beams (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 μm 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.

5.3. Array printing with discrete laser optical systems

The Polariod Helios system is an example of a laser printer in which assemblies of discrete lasers have been used in combination with free-space optics to assemble laser thermal printing heads. As an alternative, Presstek, Inc. 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 was formed from an ensemble of lasers and associated optics assembled across the length of the printing drum.

This approach, which was used in the Heidelberg Quickmaster DI printing press, has the virtue that the laser beam-shaping optical systems are inherently simple. As shown in Fig. 12, the light from an IR laser diode is collected by a collimating lens and focused onto the input end of an optical fiber by a coupling lens to form a fiber pigtailed laser unit.[13] The light exiting the optical fiber is collected and focused onto the media by a similar two-element lens output optical system. Preferably, the laser emits light with a small divergence (NA < 0.3), to maximize the depth of focus at the media. As is typical in the laser thermal systems, the laser emitter puts out light with both a low NA and a large NA (>0.3). To compensate, the fiber input optical system could use a divergence-reduction cylinder lens (not shown) located prior to the collimator to modify the fast-axis light. Depending on the design, this printer can produce printed spots between ~12.5 μm and 50 μm in size. Alternately, to avoid optical fiber coupling losses, as well as any induced optical fiber related beam noise, the system can focus the light directly onto the media, rather than onto an optical fiber.

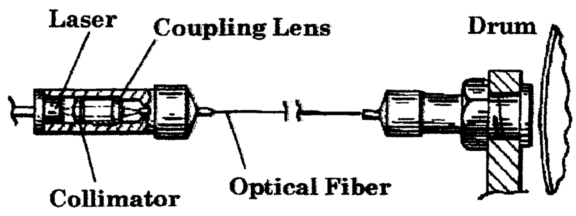

Fig. 12. Printer with a synthesized laser array having fiber coupled lasers. U.S. Patent 5,351,617.

Presstek has developed alternate print-head technologies to that shown in Fig. 12. In one case, the directly addressed IR laser acts as a pump laser to an external laser crystal.[31] The 808 nm pump laser light encounters a cylindrical microlens and a spherical focusing lens, which together focus the pump light on 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 TEM_{00} 1064 nm output beam that is focused on the media by a focusing objective lens. The reduction in the beam divergence compared to 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.

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 provided a compact optical head with replaceable individual laser diodes.

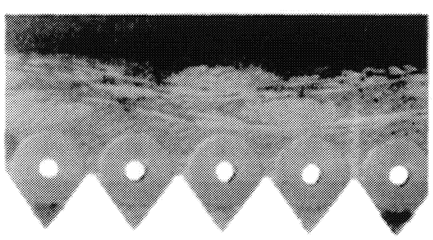

Fig. 13 Portion of the end face of a V-groove optical fiber array.

The fiber-array print-head printer was developed[10,14,32], using a series of butt-coupled fiber-pigtailed diode lasers, individually spliced to single-mode optical fibers (5 μm core). The print-head optical fibers were brought together in a pattern of adjacent V-grooves (see Fig. 13), and the fiber exit faces were re-imaged to the media by a print lens. In order to reduce the spot pitch (increase the optical fill factor), the single-mode optical fibers are progressively etched down from the initial 125 μm diameter cladding, to a mere 18 μm diameter. The V-grooves, which were etched[33] into crystalline silicon, provided a series of progressively smaller V-groove structures to hold the etch-reduced optical fibers. While this approach works, low optical efficiency and channel noise sensitivity made it impractical for laser thermal printing

The APPROVAL™ Digital Color Proofing system print-head[34,35] uses a similar architecture, except the single-mode lasers and single-mode optical fibers were replaced with multimode lasers and multimode optical fibers. Figure 14 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 cylinder lens into the individual multimode optical fibers (NA ~ 0.24) to yield fiber pigtailed lasers with ~400 mW output per fiber. Although the fiber supports 0.24 NA light, ~90% of the coupled optical power is contained within a generally Gaussian beam with a NA ~0.12. The pigtailed optical fibers are coupled into the print-head optical fibers (also NA ~ 0.24) by means of standard industry ST connectors, which have a high positioning accuracy.

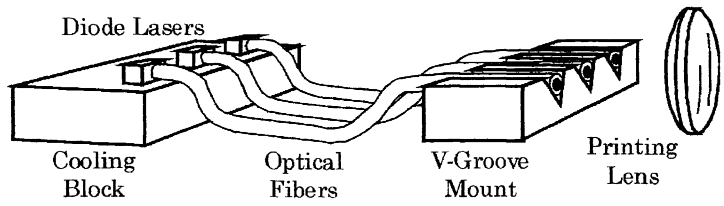

Fig. 14. Printer with a laser array synthesized from discrete fiber-coupled laser diodes and a V-groove fiber mount. US Patent 4,911,526.

The multimode print-head optical fibers are glued into V-grooves at 130 µm spacing between centers. The end face of the V-grooves is polished to provide a smooth and co-planar output surface. A printing lens, working at a demagnification of 2.2:1, images the array of fibers onto the drum. 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 numerical aperture light overfilled the print lens, and was thereby clipped. As it operates at a modest magnification, the print lens supports relatively large fields and numerical apertures at both the object (fiber array [~2 mm field and ~0.12 NA]) and image planes (~1 mm field and ~0.264 NA).

This print-head can also be tilted at an acute angle to increase the apparent print-head resolution by compensating for the gaps between the optical fiber cores.[11] The data for each channel is digitally delayed to align pixels to a line normal to the fast-scan direction on the proof. Printing systems with both 30 and 64 channels have been built.

6. A MONOLITHIC SUBARRAY MULTICHANNEL PRINT-HEAD

As an alternate approach to reducing print-head cost, a print-head was developed Eastman Kodak Company using a laser array with multiple addressable groups of single-mode diode lasers on the same substrate[36]. The associated optical system[36,37] provides a sophisticated design employing multiple micro-lenslet arrays and spot and pupil re-imaging 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.

The key attribute of the monolithic multichannel print-head is that it uses a directly addressable laser diode array consisting of laser subarrays, which allow the system to provide source redundancy without resorting to an external modulator array. The optical layout[3,37,38], shown in Figs. 15 and 16 uses an array-direction intermediate-imaging concept in which the respective beams from each of the addressed sub-arrays are collected into a printing beam, and the ensemble of printing beams are imaged to the media.

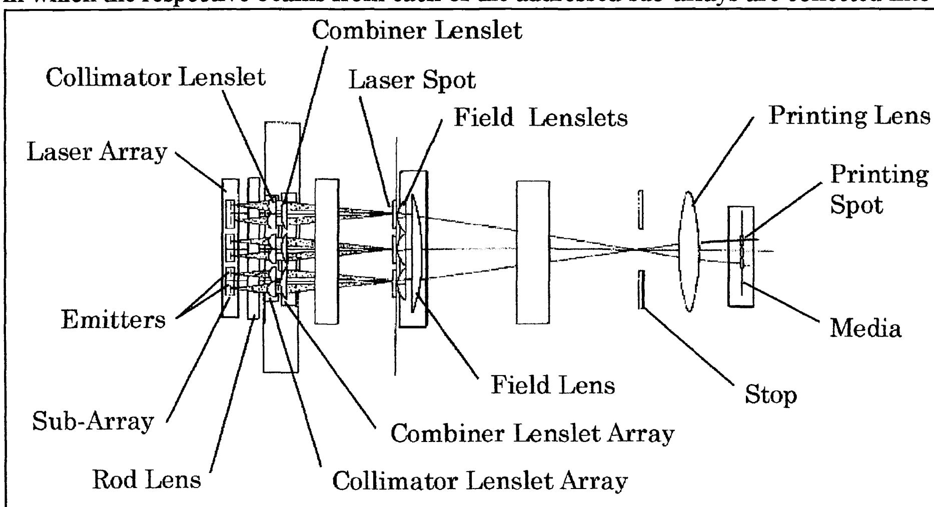

Fig. 15. Array-direction optics of a laser printer with addressed laser emitter subarrays. U.S. Patent 5,619,245.

The laser diode array[36] comprises 160 single-mode, 835 nm diode lasers gathered into 10 subarrays, which are separated by 250 µm spacings. Each channel, which is composed of 16 mutually incoherent single-mode diode lasers spaced at 50 µm intervals, is 750 µm wide and driven by its own current driver. Thus, the total length the array is ~10 mm. The fill factor of the laser array is very low (~6%); therefore, the design needs to increase the fill factor to ~100% at the medium, while providing good light efficiency. Additionally, all 16 single-mode lasers in a subarray must combine into a single printing spot in order to provide redundancy in the case of the degradation or failure of an emitter. If an emitter fails, the others can compensate for the power loss by slightly increasing their emitting power.

In the array direction, the print-head[37,38] uses a series of refractive lenslet arrays and field (or combiner) lenses to direct the channels of beams onto the media. The array-direction optics use a classical object-to-image conjugation approach, intertwined with pupil-to-pupil conjugation, to obtain the image without loss of brightness. Each of the 16 laser emitters in a given laser subarray is collimated by a collimator lenslet (see Fig. 15, where two laser emitters are shown per subarray). 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 subarray in overlapping fashion, to telecentrically image 10 separated beams (channels) at an intermediate image plane. In combination, the combiner lenslet (EFL = 50 mm) and a collimator lenslet (EFL = 200 µm) magnify a ~4 µm wide emitter by ~250X to an ~1 mm wide image. The 16 collimated beams are directed into the input aperture of the respective combiner lenslet, such that the ensemble of beams fill the aperture of the combiner lenslet and form a combined Gaussian beam at the image plane. Although a given emitter has a miniscule NA (~0.1/250), the composite NA from the ensemble of laser beams is relatively large (~0.1).

The media could be co-located at the image plane occupied by the imaged laser spots, except the spot size and the pitch may not match the printing specifications. A printing lens can be used to re-image the laser spots onto the media plane. As shown in Fig. 15, a field lens near the intermediate image plane diverts the beams so that they pass through the printing lens aperture stop. If only this field lens was used, 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 without affecting central channels. This problem is remedied[38] with the addition of another lenslet array, consisting of field lenslets. Each of these lenslets re-images a corresponding combiner lenslet to the plane occupied by the aperture stop, thereby superimposing the combiner lenslet's images at the stop and equalizing the vignetting across the channels. As a result, the printing lens images the field lenslet array onto the medium and the overall system light efficiency is improved to nearly 70%.[39] As each field lenslet is 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 de-magnifies at 1/40X, telecentrically presenting a row of 25 µm spots to the media.

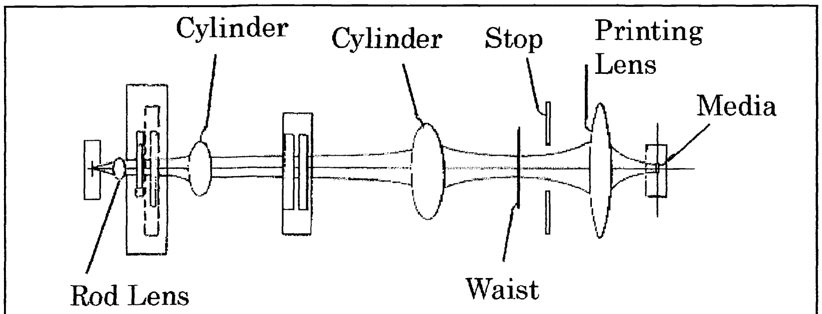

Fig. 16. Cross-array direction optics of a laser printer with addressed laser emitter subarrays. U.S. Patent 5,619,245.

The cross-array optics, shown in Fig. 16, use a variety of cylinder lenses to shape the beams, providing Gaussian beam waists near the aperture stop of the printing lens, and again at the media plane. The single-mode light is first collected by a rod lens, which reduces the numerical aperture of each beam. The system can form either a round spot or an elliptical spot, according to the relative magnifications in the array and cross-array directions. A 2-cylinder lens system in the cross-array direction produces an elliptical spot with a 2:1 aspect ratio on the media, whereas a 3-cylinder system produces a round spot. This system can also be outfitted with a smile corrector,[23] positioned near the combiner lenslet array, to provide a dramatic increase in the effective depth of focus at the media plane.

7. LASER ARRAY AND MODULATOR ARRAY SYSTEM

The printing systems discussed previously are limited to providing a handful to <100 printing channels because of laser or system packaging constraints. For those applications, which require hundreds, or even thousands, of printing channels, different system architecture is needed. In this case, the preferred system architecture uses an integrated print-head wherein laser light illuminates a spatial light modulator array, which is subsequently imaged to the media plane. Obviously, the design and performance of such systems is very dependent on the properties of the spatial light modulator array. This design space was first extensively developed by Xerox Corporation,[40,41] which developed a complete solution including laser array sources, a viable modulator array technology, and the basic optical system configuration. Subsequently, several products, including the Creo Trendsetter thermal plate setter and the KODAK POLYCHROME GRAPHICS TH80 Newsetter for newspaper printing have been developed.

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. The system was enabled by the total internal reflectance (TIR) modulator,[42,43] shown in Fig. 17, in which pixels are formed via individual patterns of electrodes on the top surface of an electro-optic substrate. The electrode patterns provide a structure of alternating-polarity electrical-fringe fields when voltage is applied. These electrical fields penetrate the electro-optical substrate (lithium niobate (LiNbO3), for example) to produce localized changes in the indices of refraction. Phase differences are imparted to the transiting light beam that result in diffraction patterns when the light is directed to a Fourier plane within the printing lens. When proper Schlieren spatial filtering is applied to discriminate between the light patterns of the modulated and unmodulated light, this system provides an addressable array of pixels when the modulator array is imaged onto the media plane. As the initial Xerox systems[41] 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, because side lobe interactions were reduced. For optimal operation of the modulator, light must be at grazing incidence at the electrodes. As shown in Fig. 17, the input and exit faces can be cut at an angle to enable an in-line optical system configuration.

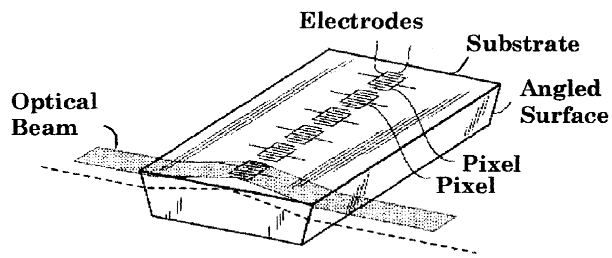

Fig. 17. The linear TIR spatial light modulator.

The Xerox system,[41,44] shown in Fig. 18, 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 laser source outputs a single beam, which is collimated in the array direction onto the modulator array. A three-element anamorphic optical system was used in the cross-array direction to focus the light to the modulator array. In the case that a Gaussian beam laser source was used,[41] the illumination system could be equipped with an apodizer to make uniform the array-direction spatial-light profile to within a few percent but at the cost of a 50% light loss.

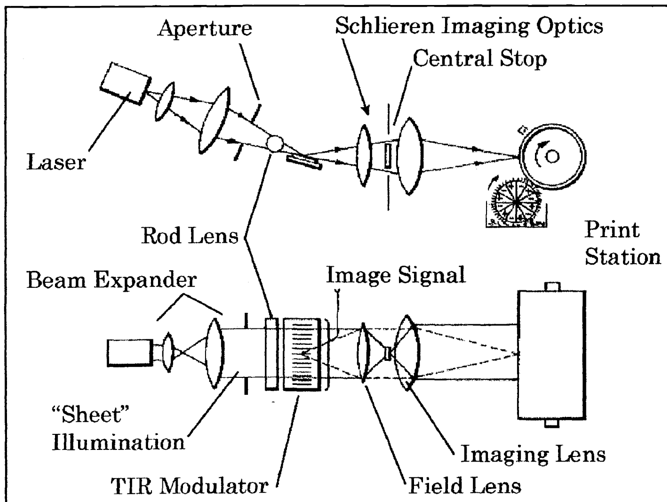

Fig. 18. The Xerox printing system with TIR modulator array.

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

7.2. Spatial light modulators

Aside from the Xerox TIR modulator technology, several other modulator-array technologies have potential application in this type of system. Candidate-device technologies include polarization modulators (such as PLZT), acousto-optic modulators (AOMs), digital mirror array modulators (DMDs),[45] micromechanical grating modulators,[46,47] and electro-optic grating modulators.[40,42,43,48,49]

For this type of system, 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 ~1 kW/cm^2. This laser beam power density is rather high and depends on modulator-pixel size, fill factor, and optical efficiency. The modulator must also provide a minimum contrast ratio of ~10–25:1 (the ratio of channel "on" irradiance to the channel "off" irradiance) and work well in the near infrared. In addition, modulated beam rise- and fall-times should be less than ~2 μsec. A high optical fill factor (nearly 100%) is a necessity.

It should be noted that the length of the modulator array and the allowed numerical aperture for optimal response (modulation contrast, minimal crosstalk, etc.) might constrain the array direction Lagrange supported by the system. Also, to enhance the uniformity of the response across the modulator array, the laser beam-shaping optics may be required to present the modulator with spatially uniform and telecentrically oriented incident light. Similarly, in the cross-array direction, the modulator response characteristics may constrain the system Lagrange, including the amount of laser smile tolerated. In general, in the cross-array direction, the light is focused to form a beam waist at the modulator, which is confined within a narrow width corresponding to the defined active height of the modulating pixels.

7.3. An array print-head with a fly's eye integrator

One laser thermal printing system[50,51,52] that combines a laser diode array light source, a spatial-light modulator array, and light-uniformization means, is shown in Fig. 19. The print-head, developed by Eastman Kodak Company, combines 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 the array direction, the fly's eye integrator telecentrically flood illuminates the spatial-light modulator array with uniform light, while the cross array light is focused to form a beam waist at the modulator. In combination, the anamorphic 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. The illuminated modulator is telecentrically imaged to the media plane by the print lens. Depending on the type of modulator used, such as polarization or Schlieren, filtering means would be positioned in the vicinity of the printing lens, as appropriate.

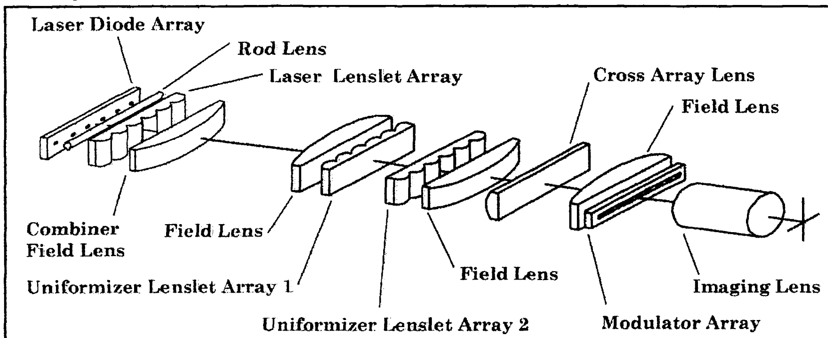

Fig. 19. Laser printer utilizing fly's eye optical integration to illuminate a modulator array. U.S. Patent 5,923,475.

In greater detail, the array-direction illumination optics (the laser lenslet array, the combiner field lens, several field lenses, and two uniformizer lenslets), as illustrated in Figs. 19 and 20, collect light from each emitter, magnify and redirect it, illuminating the entire length of the modulator array. 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 overlap image over the full length of the modulator array. The image conjugate relationships in the system are shown: planes a_0, a_1, and a_2, are conjugated to each other, as are planes b_0 and b_1 to each other. 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. First, the laser lenslet array, with N_1 lens elements (one per emitter) and the combiner field lens, overlap image the beams from each emitter to an intermediate illumination plane a_1. While this light has been overlapped, it has not yet been mixed angularly or spatially. As a result, any systematic problems in the light profile across the emitters, such as the edge rolloff shown in Fig. 2, are not removed, although such effects are averaged.

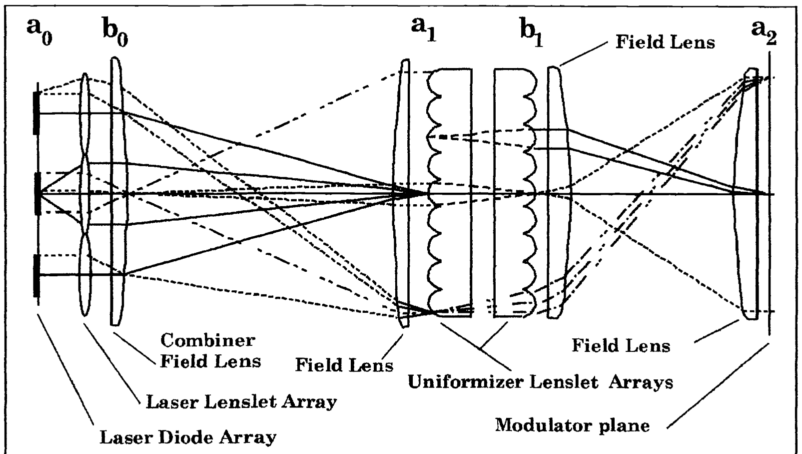

Fig. 20. Light transfer within the fly's eye integrator optical system.

Thus, a second integration stage, the fly's eye integrator, is used. The pre-uniformizer field lens provides telecentric illumination at the intermediate plane a_1. The light profile at the plane is parsed into N_2 beams, corresponding to 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 post-uniformizer field lens of Fig. 20 to image the lenslets of the first uniformizer array in a magnified and overlapping fashion onto the a_2 plane (the modulator 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 exemplary OptoPower OPC-A020 laser 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 Fig. 2). The cross-array direction light is a highly divergent Gaussian single-mode beam (NA ~ 0.63). The laser lenslet array (2.47 mm EFL) reduces the array direction Lagrange, by effectively removing the spaces between emitters (~0.187 mm 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 plane to fit within the manufacturing constraints (size limitations on lenslet width and the overall size of the array, or limitations on the sag height of the power surfaces) of the uniformizer-lenslet array.

This system used a modulator array with 256 pixels, each 63.5 μm wide, for an overall device length of 16.25 mm. The design numerical aperture (NA) at the modulator plane was 0.023. The uniformizer-lenslet arrays, which were identical, each comprised six cylindrical y profiled lenslets, each 1 mm wide. The combiner field lens had a nominal focal length of 99 mm, filling the 6 mm overall width of the first uniformizer-lenslet array 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 post-uniformizer field lens provided the appropriate magnification to illuminate the full length of the modulator array. The print lens de-magnified the modulator array at (1/6)X to provide a 2.7 mm wide line of printing spots with an array direction NA of ~0.14.

In practice, a ~±6% uniformity at the modulator array was provided with this system, although better results are achievable. System light efficiency in the main beam at the modulator plane was ~69%, with minimal light lost to the side lobes cast by the fly's eye integrator.

The cross-array optics of this system included a rod lens that was mounted to the diode laser assembly and a set of cylindrical lenses to provide a Gaussian beam waist at the modulator array, fitting the light within the pixel height. Smile correction was used to effectively reduce the laser smile from ~10 μm to ~2 μm residual.

7.4. Alternate array print-head designs

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 printing system (see Fig. 21) with array-direction light homogenization using an integrating bar[53] has been described by Kodak Polychrome Graphics. Integrating bars, or light pipes, operate by a process of total internal reflections to overlap and homogenize the light traversing their length. These bars are generally dielectric, rectangular structures with the input and output faces at the opposing ends. The degree of uniformization is largely dependent on the length of the integrating bar and the numerical aperture of the input beam. If the input light fills the input face, light uniformization can occur without any significant loss of source brightness. The system is configured to image the exit face in the array direction imaged to the modulator plane. Conversely, the cross-array direction light underfills the integrating bar and propagates at a low numerical aperture, such that it sees the integrating bar as a thick window, and not as a uniformizer.

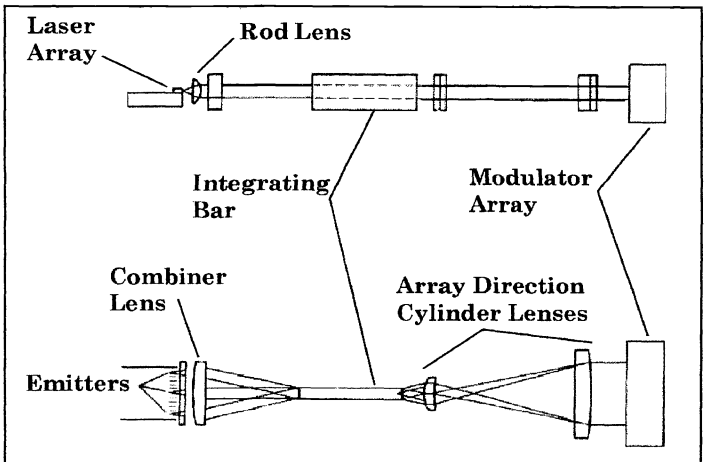

Fig. 21. Laser printer illumination of a modulator array, by means of an integrating bar. U.S. Patent 6,137,631.

As another example, an IR (850 nm) laser thermal printing system[54] 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, to compensate for the edge rolloff. This approach, developed by Daniel Gelbart of Creo Incorporated, as shown in Fig. 22, has a modified critical-type illumination system[30] that potentially corrects the macro nonuniformities (rolloff) in the array direction. However, this approach may have little benefit in smoothing out the micro-nonuniformities, and will also only work well when the light profile is generally symmetrical. Additionally, the system brightness is decreased somewhat because of the increased array direction angular spread of the illumination to the modulator. In the cross-array direction, the rod lens focuses the light onto the modulator plane. The printing lens relays the beam focus to the media plane. As shown, the modulator is a polarization-type device (a PLZT modulator), and the system uses a polarization prism to distinguish between the modulated and unmodulated light.

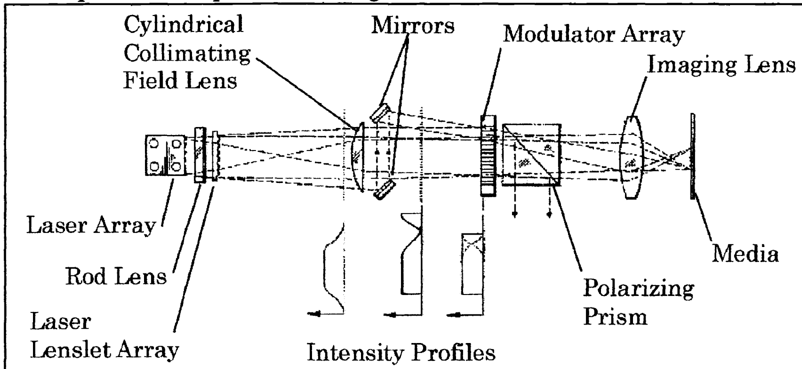

Fig. 22. Laser printer utilizing two mirrors to improve illumination uniformity to a modulator array. U.S. Patent 5,517,359.

This system[54] also utilizes the potential simplification of combining the laser lenslet array and combiner field lens into a single element.[55] 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. Additionally, the pitch of the laser lenslet array is slightly smaller than the emitter pitch (the scale of Fig. 22 obscures this detail) on the laser array (776.3 μm vs 787.5 μm, for example), using the lenslets as off-axis imagers, relative to the optical axis of the system. This off-axis imaging causes the magnified images to shift inward, overlapping the magnified images 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 axes of the lenslets shifted appropriately.

Modulator array-type printers[56,57] have also been explicitly developed for use with the grating light valve (GLV) modulator,[46] as well as with AOM modulator arrays.[58] In one instance,[58] a single high-power laser beam 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, allowing each modulator pixel to receive an individual beam. In another system,[59] an AOM array is flood illuminated by one or two laser sources, which may either be 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.

8. OPPORTUNITIES AND CONCLUSIONS

The laser thermal print-heads that were developed for laser thermal printing 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. 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.

As new components emerge, there will be further opportunities to design higher performing and/or lower cost systems. For example, optically pumped fiber lasers could be a useful high-power laser light source for these types of systems. Furthermore, there are new market opportunities beyond laser thermal printing, such as color laser image projection[60,61,62] and organic LED device manufacture[63] that can potentially benefit by the design approaches and solutions developed to support laser thermal printing.

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