

A High-Resolution Laser Thermal Lenticular Printer

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Abstract

Lenticular printing is a method of generating 3-D, or moving, images by placing multiple image frames behind a series of cylindrical lenses. Lenticular images have been around for decades as exemplified by the kids give-away cards, which typically contain two still images.

In this paper, we present a novel method for generating lenticular images based on the laser thermal process. A high-power infrared multimode laser is used to thermally transfer dyes from three donor sheets (cyan, magenta, and yellow) to a lenticular card. The beam is oriented and aligned to the cylindrical lenses to allow a minimum spot size in the cross lens direction. The printing resolution is asymmetric at approximately 2500 by 300 dpi. This method allows the printing of 10 micron continuous tone lines, which yields 34 images behind a 75 lenses per inch substrate. Printing occurs in alignment with the lenticules by premeasurement, rotational alignment, and adjustment of relevant parameters.

The printed card is then thermally laminated with either a transparent or reflective backing, which acts as a receiver and protection. The current printer allows individual cards to be printed in less than 5 minutes. Samples will be presented, which show the high-quality motion and stills possible by this process.

Introduction

It has long been desired to have direct view pictures, which contain either 3-dimensional or limited motion. Although current technology allows motion on dynamic displays, the costs are high, and the need for a power supply limiting. Holograms are one method of generating the necessary passive multiple images, but suffer from needing a point source illuminate and the complexity of generation. Lenticular imaging is a technique whereby an array of cylindrical lenses (lenticules) is used to direct different images in different directions. Lenticular imaging achieves multiple images while not needing a power supply nor requiring special illuminants.

Lenticular images have been available for many years, as exemplified in the two images give away toy cards. The perception was that high-quality images were not possible and that lenticular cards are strictly toys. Recently, Matsushita Electric Industrial Co., Ltd. introduced a motion imaging printer that writes multiple images on a lenticular substrate using a thermal dye transfer print engine.[1,2] The images are quite striking and allow 6 images at 100 dpi to be written. The six images have significant ghost images from adjacent images so small changes such as motion or 3-D depth work best.

To increase the number of images on a card, one must decrease the writing line width or decrease the number of lenticules per inch on the card, which has a concomitant change in the image quality. Resistive head thermal dye transfer allows only about 600 dpi and therefore, the resolution is limited. Laser thermal dye transfer has been demonstrated to much better than 2400 dpi and numerous manufacturers use laser thermal print engines for the graphic arts industry for proofing and plate writing applications. Although lasers have been used in electrophotography and silver halide writers, there has been a lack of implementation of lasers in consumer thermal applications. This has been due to the high cost of the printhead.

The advent of laser diodes has allowed lasers to become more ubiquitous. Routinely, low-power diode lasers are now used in laser pointers and desktop laser printers. High-power diode lasers are also now becoming cheaper. Diode lasers also have the advantage of being reliable and directly modulatable, ideal characteristics for a consumer product. We report here the development of a relatively low-cost laser thermal imaging printer, which can write very high resolution lenticular cards.

Printer Optics and Mechanics

High-power diode lasers (>200 mw) have wavelengths in the infrared and use an emitting stripe or series of stripes to yield the high power. The emission is from a thin layer. This thin layer can only support a single spatial mode along the narrow axis. Many spatial modes are generated along the long axis (stripe direction). Figure 1 shows the output of a typical high power laser diode. The consequence of this asymmetry in output size and number of spatial modes is that diffraction limited focusing is only possible in the direction in which a single mode occurs. The smallest spot that can be formed, while retaining the power, is an elliptical beam. Figure 2 shows the spot that is generated and its

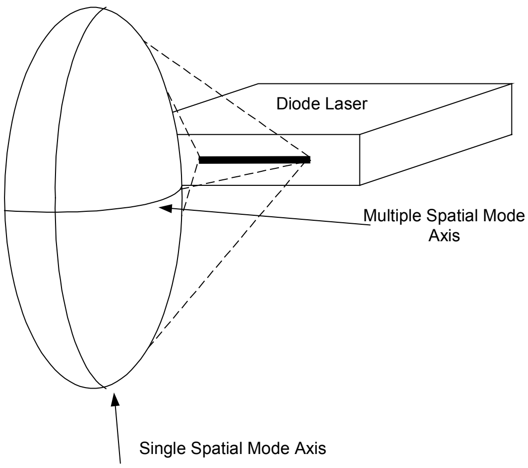

Figure 1. Output of a high power stripe diode laser.

relationship to the diode laser. In the figure, one can see that the spot has a high aspect ratio. Fortunately, this is exactly the beam shape that is desired for use in a lenticular printer.

Figure 2 also shows the layout of the optics, the orientation of laser spot, and the direction of transport in the laser printer. An SDL, Inc 1-watt diode laser (model 5400 C-mount laser) is used as the laser source. This diode laser has a nominal operating wavelength of 830 nm. The output beam is beam shaped, oriented, reflected off a galvanometer, and imaged on the media through an F-theta lens. All optics are antireflective coated for 830 nm to reduce power loss. The output of the laser is imaged onto the writing plane to yield a spot that is approximately 17 micron by 80 microns ($1/e^2$). The galvanometer mirror scans the beam such that the long axis is always parallel to the scan. The galvanometer and F-theta lens combination was constructed to give 3.5 inches of scan.

Although the laser beam is 17 microns wide, the actual written spot is about 10 microns wide corresponding to 2540 dpi writing capability. Figure 3 shows three, single-pixel written spots. The spots are a red, green, and blue pixel separated by a single line each. Two donors are required for each of these pixel colors. It is easy to see the asymmetry of the pixels. The picture is a view through a transmissive backing after fusing. The reason the written spot is smaller than the laser beam spot size is that thermal media is threshold driven. Threshold driven in thermal media refers to an initial amount of energy going into heating the dyes and support before any transfer can occur. Thus much of the tails energy profile of the 17 micron beam does not heat the media enough to cause dye transfer. The amount of transferred dye is dependent on the intensity of the laser beam and therefore, continuous tone images are readily accomplished. Only small changes in the width of the line will occur as the intensity is increased and may be ignored.

The stage is a low-cost high-resolution transport stage. A stepper motor rotates the lead screw and moves the stage holding the card at a constant velocity during printing. A

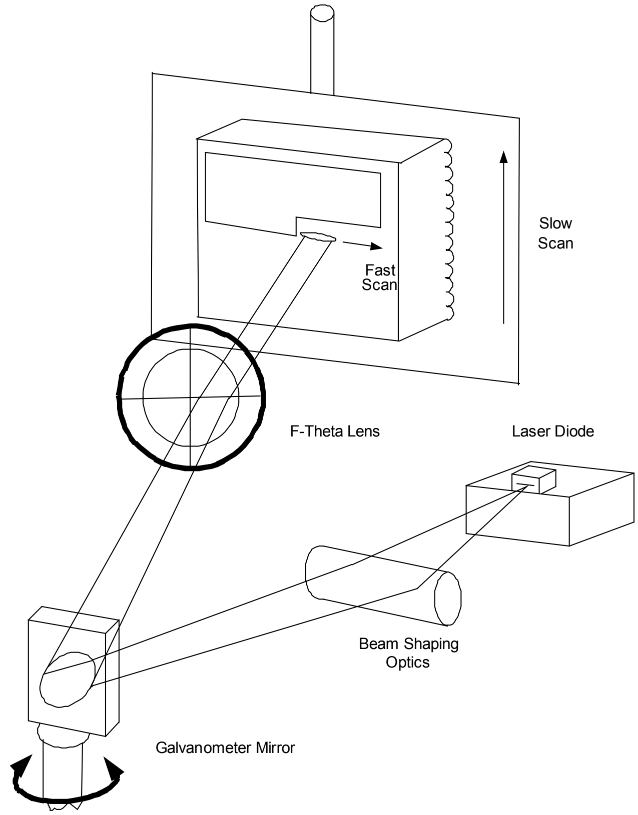

Figure 2. Schematics of the optics and transport system of the laser thermal lenticular printer and the orientation of the writing beam.

small rotational capability is incorporated into the stage to allow alignment of the lenticules to the writing beam. The range of rotation is approximately 3 degrees. The constant velocity is calculated to obtain the proper viewing distance based on the card parameters measured, as detail later. The calculated velocity incorporates the frequency of the galvanometer into the calculation.

Measurement of the accuracy, velocity, and speed of the stage has shown that the stage is never more that ±2 microns from its theoretical location, based on the specified velocity, throughout the range of stage travel (70 mm). This is adequate for a printed line resolution of 10 microns.

The laser beam is linearly scanned over the donor sheet and turned off during the retrace time. Scanning the beam linearly across the F-theta lens results in the dwell time and spot size of the incident laser beam being constant throughout the scan. The retrace time is minimized to increase the writing efficiency. The writing efficiency is defined as the percentage of time actually spent writing a line to the total of the writing time and the retrace time.

The printer specifications are shown in Table 1.

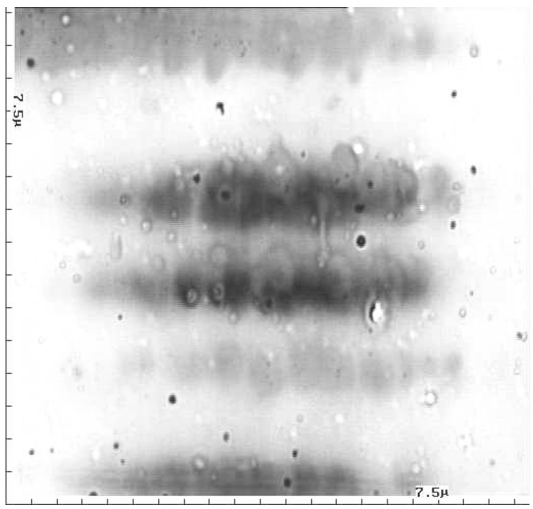

Figure 3. Three single pixels formed from two donor colors separated by one line each. The top pixel is red (M+Y), the middle pixel is blue (C+M), and the bottom is green (Y+C).

Table 1. Printer's specifications.

Laser power	1 watt
Rotational alignment resolution	0.006 degrees
Pitch measurement	150 PPM
Center view location	5 micron
Written line width	10 micron (2540 dpi)
dpi along scan	300
Gradation (bit depth)	8 bit per color per pixel
Number of donors	3 (cyan, magenta, and yellow)
Laminate	Clear or white transfer laminate
Galvanometer frequency	106 Hz
Writing efficiency at 106 Hz	68%
Time per color	1 minute
Card size	2.5 by 3.5 inches (63.5 mmby 88.9 mm)
Card pitch	50 or 75 lines per inch
Time to write full card	3 minutes
Complete time to write a finished card	<5 minutes
D-min Reflective	0.1
D-max	2.0

Alignment

Lenticular media must be aligned carefully to the image lines for high-resolution images. Image degradation will occur if any one of three misalignments occur. First, the image lines must be parallel to the lenticules. A small angular misalignment will cause the images to wipe diagonally across the card, while a large misalignment will give angular stripes. Another critical alignment is the relative pitch of the image lines to the pitch of the lenticular card. Alignment at exactly the same pitch yields images that are only viewable at infinity. A slightly larger pitch for the image lines relative to the lenticular card will focus the image lines relative to the lenticular card will focus the individual images closer. By proper control of the relative pitch, the proper viewing distance can be placed at a position that most people hold the card (12-18 inches).

Finally the center view should be controlled. When the images lines are placed behind the lenses there is a phase difference, which can be adjusted to determine which image is viewed at the normal position. It most cases, it is desirable for the normal incident image view to be the center of the motion sequence. As one moves away from normal, the optical aberrations become higher and therefore, for maximal average quality through a motion sequence, the center image should be the normal incident view. This position corresponds to the center image slice being placed behind the center of the lens closest to the middle of the card.

To achieve the necessary alignment the cards are pre-scanned to measure the relevant parameters. The rotational alignment is achieved by conducting an initial rotational alignment to within a half a lenticule maximum misalignment. A laser beam then irradiates the lenticules as the media is transported. A photodetector placed behind the card detects periodicity of the lenticules on either end of the card. The relative phase difference in the periodic intensity is used for a final rotational alignment.

The periodicity is then remeasured after rotational alignment to obtain the pitch of the lenticule and the absolute position of the center of the center lenticule. With this information all necessary information is available to print the card.

Media

There are three types of media used in the laser thermal lenticular printer. The injection molded lenticular media is the support to which the image is applied. Three donor sheets are needed (cyan, magenta, and yellow) to generate a full color image. Finally, there is a laminate, which is applied over the image for protection and acts as a binder for the dyes. It also, in the case of reflective cards, acts as a reflection layer.

The lenticular cards are injection molded out of polycarbonate from a precision machined mold to give a highly reproducible card with an excellent profile and sharp cleft between lenticules. Banding and uniformity of the lenticules must be carefully controlled or image degradation can become significant.

The design of the lenticular card's optics is important for good image quality and ease of use. There is a tradeoff between the F# of the lens, the lenticules per inch (lpi), and the viewing angle. The LPI determines the dpi of each individual image in the cross lenticule direction. Typical values range from 25 to 300 with 50 to 100 being the most common. The F# determines the thickness of the card, for a specific refractive index, and also the viewing angle. The viewing angle is the angle over which distinct images may be viewed before repeating because of vignetting. A low F# requires a thinner support, but gives a wider viewing angle. The quality of the images furthest from normal are also degraded more due to aberrations.

Measurements conducted on the injection molded cards have shown that the pitch of the lenticular card may be maintained to within less than 150 parts per million (PPM). Two different types of cards were made. One type of card has 50 lenticules per inch with a thickness of 0.050 inches yielding an F# of 2.5. This card has a viewing angle of 36 degrees. The other card had lenticules with a pitch of 75 LPI and a thickness of 0.030 inches, giving a viewing angle of 40 degrees and an F# of 2.25.

The donors consisted of a cyan, magenta, and a yellow donor on 0.004-inch thick polyethylene terephthalate support. The coatings were generated in a similar manner to that described previously.[4] The donors consisted of a thermally transferable image dye, gelatin as a binder and carbon as an infrared absorber. The dye laydown is sufficient to achieve a 2.0 transferred optical D-max. Beads of about 5 microns in diameter were incorporated to act as a spacer between the donor and receiver.

Upon laser thermal transfer to the lenticular media receiver, the dyes deposit as an amorphous to crystalline deposit, which is easily abraded off or smeared. To protect loss of the dyes and to prevent unwanted crystallization the dyes must be fused into a polymer. This can be accomplished readily by thermally laminating a polymer over the dyes. The thermal energy drives the dyes into the laminate thereby decrystallizing the dyes and providing a constant color. The laminate also serves to protect the dyes from abrasion and finger oils.

Most consumers tend to like reflective prints and this is true for lenticular cards as well. The laminate can also act as the reflective material with the incorporation of a scatterer such as TiO_2. The cards can be generated as either transmissive or reflection by changing the back laminate.

The laminate must be applied to the back in such a way to not extend beyond the card. There are a number of methods, which may be used to accomplish this goal. One method is to accurately align precut laminate and then heat. This method is difficult if alignment needs to be very accurate. Another method is to laminate a larger piece of laminate and trim. There are many laminate products, which use this approach, but it suffers from the need to trim. The other problem with both these approaches is that if the laminate support is very thin wrinkles can occur, while if it is thick, warping of the card tends to occur due to differences in thermal expansion.

The approach we have taken is to apply a transfer laminate that peels cleanly from the laminate support upon thermal lamination. The thin layer has little propensity to bend the card while allowing a clean edge with no active trimming. The card is complete upon lamination.

The Printing Process

The images can be obtained from numerous sources. For three-dimensional views, multiple images from different directions must be acquired. Motion images may be obtained from burst cameras, videotape, digital video cameras, or completely computer generated. Multiple still images can be used after appropriate resizing. Any special effects are then applied to the images. Interlacing of the images are conducted to generate the raw printable files. The number of frames (or lines per lenticule) (which are printed) are ~48 for the 50 lpi cards and 32-34 for the 75 lpi cards. Once the raw file is generated, consisting of cyan, magenta, and yellow records, a lookup table is applied to yield the proper laser power levels. Printing can occur from this file.

Printing is conducted by placing an injection molded lenticular card on the vacuum platen and applying vacuum to hold down the card. The card is rotationally aligned. The pitch and center view location is measured and used to generate the appropriate printing parameters.

A piece of donor is placed against the lenticular card. Vacuum is applied to hold down donor to the card. The image is written with the laser focussed through the rear of the donor, thereby transferring the dyes to the card. The vacuum is released from the donor, while maintaining vacuum hold on the card, and the donor removed. This process is repeated for the remaining two colors.

The vacuum is removed from the card and the laminate placed against the card over the transferred dyes. The card is transported against a heated roller, which fuses the dyes into the laminate and adheres the laminate to the card. Upon removal of the laminate support, a fully finished card is obtained. The dyes are fully registered with the lenticules and the images are continuous tone full color giving a very high-quality card.

Results and Discussion

Numerous different types of card image effects were generated. Three-dimensional imaging cards were made in the portrait mode, due to the necessity of orienting the lenticules vertically to give each eye a different view. These gave a good sense of depth, while allowing more than one viewing angle. Morphing effects and multiple still images are possible. Six completely different images are about the limit for 75 lpi cards before the cross talk becomes unacceptable. Cross talk is a ghost image appearing when the main images are being viewed.

Full motion sequences are easily generated. Numerous issues need to be addressed to implement motion sequences to yield the highest quality cards. The ability to place many images on a card raises many questions, which have not been adequately studied in relation to conventional image output.

One interesting question is whether it is better to have many different images or only a few distinct images for a motion sequence. Different motion sequences were generated with different numbers of distinct images by printing multiples of the individual frames (e.g., 34 one-line images, 17 two-line images, or 6 four-line images with 2 five-line images). The quality of the resulting cards depended on how the viewer looks at the card. More images look better as the images are moved through the sequence, but when the sequence is stopped the images are blurry. In contrast, with few images, the motion is jerky but each individual image is significantly less blurry to view.

Another issue is the appropriate trade-off between the number of images and the lpi resolution. The comparison of 50 lpi cards to 75 lpi cards reveals that the 75 lpi cards were more desirable. This was because less pixellation and jaggedness occurred. This trade appeared good, in spite of the fact that fewer images could be placed on the 75 lpi cards. Finally, it should be noted that the quality appears substantially higher than a 75 or 50 dpi image because the dpi in the orthogonal direction is close to 300 dpi.

Most defects in the images could be attributed to three sources. The donors and laminate are experimental and contained many defects. Second, control of the laser power was not as high as desired and some heat induced power changes were observed. Finally, dust is an issue, as it can generate changes in the spacing between the donor and card receiver thereby changing the focus and spot size leading to defects.

Conclusions

We have demonstrated a high-resolution laser thermal lenticular printer. The quality of the generated images is high. We have demonstrated less than three minute print time with less than five minutes time to drop. This printer was made with all low cost components and is expected to be relatively cheap to make. The use of high-power diode lasers in a novel scanning orientation allows the use of low-cost multimode lasers.

Alignment is accomplished by pre-scanning each card and aligning based on the scan information. Rotational and pitch alignment is conducted on each card, which takes out some nonuniformity in the media and allows for a more robust system. The quality of the cards is excellent with the majority of defects currently in the media. Lamination gives a final card where the dyes have been fused and are protected. We have shown a low-cost desktop, or kiosk, based laser thermal lenticular printer is technically feasible, which prints a card rapidly and with exceptionally high quality.

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Biography

Lee W. Tutt has work in the area of light interactions with matter for over 19 years. He obtained his B.S. in chemistry from the California Institute of Technology in 1979 and his Ph.D. from UCLA in 1984 in inorganic chemistry. He worked at Hughes Research Laboratories for 8 years on laser material processes before joining Eastman Kodak Company. At Eastman Kodak Company he has worked on the physics and chemistry of the laser dye transfer and ablation processes.