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Advances in lenticular lens arrays for visual display

(Invited Paper)

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ABSTRACT

Lenticular lens arrays are widely used in the printed display industry and in specialized applications of electronic displays. In general, lenticular arrays can create from interlaced printed images such visual effects as 3-D, animation, flips, morph, zoom, or various combinations. The use of these typically cylindrical lens arrays for this purpose began in the late 1920's. The lenses comprise a front surface having a spherical cross-section and a flat rear surface upon where the material to be displayed is proximately located. The principal limitation to the resultant image quality for current technology lenticular lenses is spherical aberration. This limitation causes the lenticular lens arrays to be generally thick (0.5 mm) and not easily wrapped around such items as cans or bottles. The objectives of this research effort were to develop a realistic analytical model, to significantly improve the image quality, to develop the tooling necessary to fabricate lenticular lens array extrusion cylinders, and to develop enhanced fabrication technology for the extrusion cylinder. It was determined that the most viable cross-sectional shape for the lenticular lenses is elliptical. This shape dramatically improves the image quality. The relationship between the lens radius, conic constant, material refractive index, and thickness will be discussed. A significant challenge was to fabricate a diamond-cutting tool having the proper elliptical shape. Both true elliptical and pseudo-elliptical diamond tools were designed and fabricated. The plastic sheets extruded can be quite thin (< 0.25 mm) and, consequently, can be wrapped around cans and the like. Fabrication of the lenticular engraved extrusion cylinder required remarkable development considering the large physical size and weight of the cylinder, and the tight mechanical tolerances associated with the lenticular lens molds cut into the cylinder's surface. The development of the cutting tool and the lenticular engraved extrusion cylinder will be presented in addition to an illustrative comparison of current lenticular technology and the new technology. Three U.S. patents have been issued as a consequence of this research effort.

Keywords: Lenticular, aspheric, elliptical, lens, optical manufacturing, lens design, fabrication, diamond cutting.

1. STEREOGRAPHIC IMAGING HISTORY & LENTICULAR PRINTING TECHNOLOGIES

Throughout history, man has tried to define, draw and record the world around him. The advanced state of a society is often judged by how well these recordings are made. In 280 B.C., Euclid defined depth perception and, during the renaissance, artists added perspective to their work. Some early trails of *artificial* three-dimensional imagery were stereoscopic drawings devised by Grovanni Battista della Porta around the year 1600. In 1692, French painter Gois-Clair discovered he could achieve a multi-dimensional effect on canvas by interposing a grid of vertical laths between the viewer and the painting.

In the latter part of the 19th century and into the early 20th century, photographic stereo imaging shot by camera found new popularity. In 1832, Sir Charles Wheatstone proposed the first of several stereo viewers. Inventors like Sir David Brewster advanced the Wheatstone viewer concepts and Oliver Wendell Holmes added convex lenses as eyepieces. Pictures, either *hand drawn* or *photographically* created, with specific parallax separation were viewed with handheld stereoscopes to give the illusion of three-dimensional depths. After the introduction of the commercial handheld stereoscopic viewer in the 1950's, scenes from around the world, as well as images from movie studios such as Walt Disney Studios were brought into homes as "stereoscope images." Later during the 1950's, advances in motion picture technology popularized "anaglyphic" red-and-green polarized eyeglasses that conjured up horror of multi-dimensional images, such as in the film "Creature From The Black Lagoon." These (anaglyphic) red-and-green eye glasses then later became used to view specially created art work that was then printed in collectible comic books to create the illusion of three-dimensional depth. During the later years of 1990's, video camcorders were made available for viewers who prefer video experience in stereo, even if it requires wearing special liquid crystal goggles.

In recent years, holographic or volumetric images have been used in amusement parks, casinos, museum exhibits, and in other art forms. These images can be viewed without the assistance of supplemental viewing devices, but lack the printed quality necessary for mass commercial usage. In addition, the high cost to produce such images for volume-based commercial advertising usage prohibits continual use by advertisers. The least expensive form of holographic imagery appears frequently on consumer credit cards, but appears to lack substantial quality.

1.1. History of Lenticular Lenses & Applications

Lenticular theory predates back into the early 1900's.[1] The first images to be described as "lenticular" were produced in the 1930's by Victor Anderson. By the late 1940's, Anderson's company was producing millions of simple low-quality lenticular images per year, from postcards of woman winking at the viewer to Cracker Jack prizes, political buttons and magazine inserts.

Most recently, lenticular technology has surpassed and made great in roads as competition to the aforementioned visual technologies. Since lenticular printing is far less costly to manufacture; and can illustrate both three-dimension and several styles of animated visual effects *without* the requirement of wearing special viewing glasses, handheld viewing stereo devices, or lighted stereo projectors, it is a technology that has attracted use by many advertisers worldwide.

1.2. Depth Perception Principles of Stereo Viewers

In human vision, depth perception starts out as flat; two-dimensional images received through a lens, collected and transmitted to the brain. The retina of an eye collects only two-dimensional data because it consists of a single layer of sensors. Cues of a third dimension (depth) can only be obtained through analysis by the brain of the retinal images from both eyes. While a series of minor cues (accommodation, convergence, size gradient, etc.) provide some variable depth information, by far the most dominant cue comes from the effect called binocular disparity or binocular parallax. While avoiding an in-depth analysis of this cue, suffice it to say that horizontal displacement of the two human eyes (average interpupillary distance of 6.5 cm.) produces two slightly different simultaneous retinal images. These two-dimensional images differ because each eye records the scene being viewed from a scant different angle resulting in horizontal shifts of image points in planes in front of or behind an arbitrary reference plane. These two dissimilar images are called a stereo-pair and are the major contributor to depth perception.

Such a stereo-pair can be produced photographically by recording a scene from two horizontally displaced vantage points. Thirty-five millimeter transparencies taken with special two-lens cameras, and then shown through a stereoscopic stereo viewer are familiar to the general public, but have lost popularity due to recent advancements in lenticular printing technology.

1.3. Lenticular Sheet Fed Printing

The art of basic lenticular-sheet three-dimensional and animated images has made great progress in the past decade. The major advantage of lenticular sheet fed printing is that the three-dimensional or animated images are presented to the viewer *without the need for a supplementary handheld viewing device* and can be economically produced using low-speed, "*single sheet*" at a time production output via sheet fed offset printing presses, as compared to expensively created, one-by-one production of photographically prepared stereo-pair images viewed through handheld stereoscopes; or single photographically/digitally prepared lenticular imaged prints. Print quality of sheet fed produced lenticular appears excellent as compared to the continuous tone photographic emulsion process that is then later laminated to a lenticular lens array material.

1.4. Lenticular Web Fed Printing

With the introduction of rotary-roll web fed printing, a new major manufacturing advantage occurred compared to sheet fed printing. In addition, as described with sheet fed printing, lenticular web fed printing occurs *without the need for a supplementary handheld viewing device*. Web printing is high speed and non-interrupted print manufacturing, which is printed onto continuous web rolls of lenticular material. The web printing process now takes lenticular printing and the products it can create to a new higher advanced level never made possible before with the previous prior art technologies.

1.5. Lenticular Lens Arrays

In a recent attempt to improve the optical quality of the industry's standard printable transparent cylindrical lenticular lens material, the authors determined that prior lenticular art could be significantly improved by an improved lenticular lens design, which will enhance the final viewed printed lenticular image quality. Additionally, the new lenticular material could be used with Jacobsen's recently patented web-fed lenticular print processes to raise lenticular printing and imaging systems to a higher level.[2,3]

Several years ago, Jacobsen investigated methods to develop the most advanced, optically correct and clear printable thin-gauge lenticular lens array materials to produce high-quality lenticular viewable printed products. After careful optical laboratory analysis, it was determined that the industry-standard lenticular "cylindrical or spherical" lenses have limited optical performance properties and are similar variations of older prior art lens designs. Based upon Jacobsen's findings, Johnson analyzed the then current-art lenticular optics and determined that an elliptically-shaped lens array design should provide remarkable improvement in image quality, especially for thin-gage material. Creating the elliptical lenticular lens arrays and lenticular printable material also requires a special diamond tool having the elliptical lens profile that is used to fabricate the extrusion drum. Three U.S. patents have been issued as a consequence of this research effort, and a number of international patents are pending.[4-6]

1.6. Optical Imaging Principles & Extruded Lenticular Lens Material Manufacturing

Optical lenticular sheets or rolls are defined as a fine linear array of convex lenses with specific optical viewing characteristics commonly known as "<u>lenticular</u>". Lenticular material can be made in either single sheets or continuous web rolls containing over 40,000 lineal feet of material in one web roll. This lenticular material is produced either by extrusion, embossing, molding or casting processes via sheet or continuous webs using optical quality APET, PETG, PVC or other suitable plastic resin materials with spatial frequencies from 15 to 500 lenses per inch (lpi).

Typically, commercial quality optical lenticular lens array film material is produced via hot melt extrusion onto cylindrical engraved mandrels. This method is very cost-efficient and has the ability to produce large quantities of lenticular material. The plastic extrusion process consists of melting plastic resin pellets at high temperatures (> 500° F). Molten resin is then extruded through dies under high pressure onto a lenticular engraved cylinder, which contains the lenticular lens array pattern. The thickness of the extruded resin is carefully monitored and precalculated in order to produce the proper thickness (to achieve focus) as compared to the lenticular pitch of the lens design, which is determined by the lenticular engraved cylinder. The lens material can be provided as individual sized cut sheets or in web rolls at desired widths. The lenticular engraving cylinder is internally water cooled, can be as large as 120" long x 35" outer diameter, and can weigh as much as 5,000 lbs. Modern computer-controlled lenticular extruders can produce over 12,000 lbs of material per day.

1.7. Imaging of Lenticular Lens Array Materials

The principles of lenticular imaging are quite simple. The object, scene, or images are first recorded as a series of two or more dimensional (2D) images taken from a series of two or more horizontally displaced vantage points. Assume "n" equal the number of 2D images taken. For composition of most three-dimensional (3D) images, the number of 2D images is four to sixteen. These images are then "line-formed" behind the lenticules; i.e., "n" fine lines are recorded behind each linear convex lens on the lenticular material with each line containing only the image content of a single 2D image. When the viewer sees the final composite image, each eye views only a single 2D image. Due to the fact each eye receives a different 2D image (the two comprise a stereo-pair); depth is perceived in the scene.

Another technique that works well with lenticular material is commonly referred as "animation". Two, three, four or more totally different 2D images are recorded in differing recording (and viewing) zones. As an example, consider two conventional 2D images and lenticular print material with a 32-degree viewing angle. One 2D image is recorded on the lenticular material from a +16 to 0 degree viewing angle, while the second image is recorded on the lenticular material from 0 degree to – 16 degree viewing angle. When the viewer is positioned in the respective viewing zone or when holding the printed lenticular material at a particular tilted viewing angle, only one of the images will be visible. The lenticular material being a linear single element convex lens is not perfect. When combining images behind the lenses on the lenticular material, some ghosting can appear due to misregistration, or aberrations of the lenticules itself.

1.8. Lenticular Printed Images vs. Holographic Images & Comparisons:

Creating stereoscopic (three-dimensional) 3D projected imagery can be accomplished several ways, with the two most popular being *lenticular* and *holographic* imaging. Although they are not similar in how they appear as 3D formats, they are at times mistaken for one another. Lenticular images can be recognized by the plastic-ridged cylindrical lens covering the printed or photographic image. Lenticular images, either printed or produced photographically, tend to appear much more life-like than holograms. Since holographic images are not printed, they seem to appear as surreal art, or somehow artificial. Today, holograms are used quite frequently on consumer's credit cards.

1.9. Modern Day Industrial Lenticular Products & Applications

Depending upon the desired lenticular format, it is possible to add-on many other special effect options in-line on press, including: rotary die-cutting and removing web material, die cutting contour shapes, perforating for coupons and tear-offs, remoistenable glue for bounce backs, reply envelopes, T-shirt iron-on color printed transfers, pop-out puzzles, structural paper rising pop-ups, unusual fold sequences and format constructions, latex scratch rub-offs, ink jet imaging variable data or consecutive numbering for contests, plus special coatings, inks, papers and plastic substrates—many of which can be applied or created in just one press pass.

Corporate Brand Identity Lenticular Packaging:

- Brand Product Identification
- Entire Outer Lenticular Packaging Enhancements (Box Over wraps)
- Segmented Applied Lenticular Coverage To Outer Packaging
- Pressure-Sensitive & Self-Adhesive Lenticular Products
- Multi-Ply, Multi-Substrate Peel Open Pressure Sensitive Labels
- Lenticular Laminated To Paperboard Products
- In-Packs & On-Packs (FDA direct food contact approved)
- Beverage Cups: Decorative Partial Or Full Wraps
- Video, DVD, CD Disc Cover Lenticular Treatments.

Promotional Lenticular Products and Applications

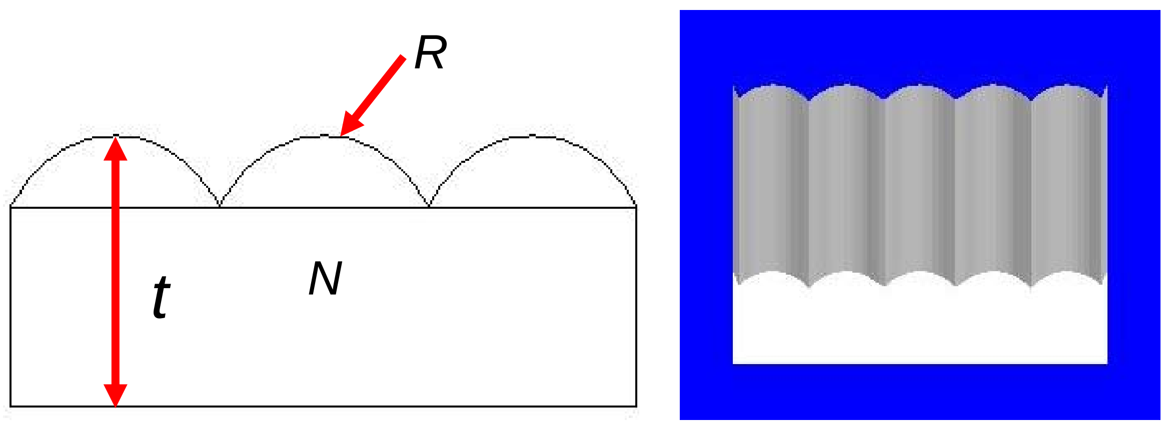
- Pressure Sensitive Adhesive Lenticular Labels
- Magazine Inserts and FSI's
- Mini-Catalogs and Mini-Comic Books
- Brochures
- Direct Mail

- Postcards
- Structural Pop-Ups
- Huge Backlit and Reflective Posters
- Kid's Premiums and Trading Cards
- Spinning Wheels and Slide Charts
- Security Game Pieces and Punch Out Puzzles
- Scratch-Offs, Fragrance Scents, Special Inks
- Ink Jet Variable Imaging of Data

Non-Imaging Uses of Elliptical Lenticular Lenses

- Rear projection TV screens
- Backlit computer screens
- Laptop computer and monitor 3D viewing system utilizing lenticular lens array and liquid crystal display technology

2. LENTICULAR LENS DESIGN



(a) (b)

Figure 1. Generic lenticular array where (a) illustrates a side view and (b) an oblique view (no scale).

As mentioned above, cylindrical lenticular lens arrays are commonly used for the purpose of specialty printing to create a 3-D effect or to encode multiple images that are singularly viewed by modestly rotating the print. Figure 1 illustrates a side view and oblique view of a typical lenticular lens array. From first principles of physics associated with optics, it is readily determined that the relationship between the distance from the vertex of the lens to the rear surface (t), upon which the displayed information is printed, the radius of the lens (R), and the refractive index (N) is given by

$$t = \frac{RN}{N-1}$$

This equation assumes an ideal lens and the distance t is also the focal length "*f*." In reality, the surface of the lenticular lens is circular in cross-section and the projected image suffers significant aberrations. These aberrations degrade the quality of the displayed image.

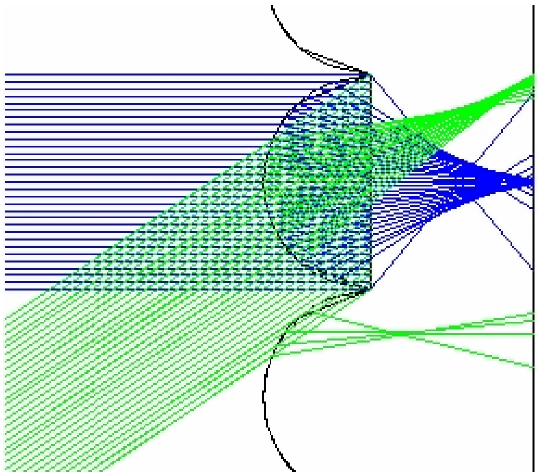


Figure 2. Cylindrical lens array.

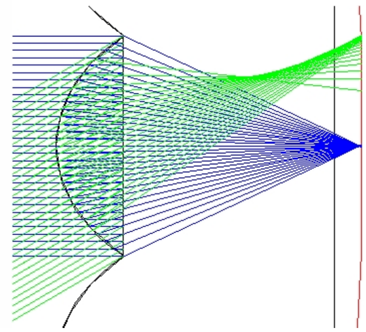


Figure 3. Elliptical lens array.

Figure 2 illustrates the induced aberrations of spherical on-axis and the addition of coma off-axis for a cylindrical lens array. In general, the light is traveling from the printed surface to the observer; however, reciprocity allows viewing the problem in reverse as well. The incident light is from a distant point source that thereby produces collimated rays. An ideal lens will focus such light to a common point of focus. As can be observed from Fig. 1, the light is spread over a significant area. This limits resolution and the number of interleaved images typical of this printing technology. It is also known by those skilled in optics that the thickness *t* will have to be less than that cited above in order to maximize the resolution in the presence of aberrations. This shortening can amount to perhaps 20% of *t*. It can also be seen from Fig. 1 that the depth of the lens surface (distance from lens vertex to intersection of the lenticules) can reach *R* at the junction of the adjacent lenses. A consequence of this is the blocking of light or the undesired redirection of light.

It is known that convex-plano single-lens elements having the image/object located in the same medium as the lens can experience correction of the axial aberration (at a specific wavelength) by changing the shape of the refracting surface to a conic having a conic constant κ given by

$$\kappa = -\frac{1}{N^2}$$

where *N* is typically in the range of 1.3 to 2 and more commonly in the range 1.5 to 1.6 for plastics used in the printing industry.[7] The conic constant for the bounding refractive index range covers from about -0.25 to -0.60. This implies that the surface shape is elliptical. The relationship between the refractive index, thickness, and radius for the elliptical lens is the same as that given above for the cylindrical lens. Figure 3 shows the raytrace for a lenticular lens having the same spatial distribution (pitch) of lenses and base radius. Notice that the axial image is essentially geometrically perfect and that the off-axis image is improved, with respect to the cylindrical lens, with coma being the dominant residual aberration. Further, it is evident that the previous blocking of some of the light is no longer a difficulty, thereby providing a brighter and clearer image. The depth of the lens junction from the lens vertex is about 60% of the former case. The use of an elliptical surface for the lenticular lenses significantly mitigates the aforementioned problems with the cylindrical lens.

The minimum pitch a given lenticular array can have using cylindrical surfaces is 1/(2*R*). When the pitch is increased, the width of the element necessarily decreases. It is interesting to note that the use of the elliptical surface can allow the use of lower pitch lenses as can be seen by comparing Figs. 2 and 3.

Specifically, the elliptical shape of the lenticular elements can be described as an ellipse having a major axis ("±*a*") and a minor axis ("±*b*"). The ellipse also has foci located at points ±*c* on the major axis. The junction point of adjacent lens elements crosses the elliptical shape at a perpendicular distance "*y*" from the major axis. The distance along the major axis from the vertex to this junction point is referred to as the sag and denoted "*d.*" The optical axis of the lenticule, which is the major axis of the elliptical shape, is perpendicular to the rear surface of the lenticular array. The vertex of the lens element is positioned along the major axis of the elliptical shape at "*a*".

Parameters for a particular application of the elliptical lenticular lens array can determine the characteristics of the elliptical shape. For example, the characteristics *d*, *t*, *y*, and *R* of the elliptical shape can be computed from the refractive index of the material forming the array, the desired pitch[1], and standard geometric equations. Accordingly, the elliptical shape is given by

$$y^2 - 2Rx + px^2 = 0, \text{ where } p = \kappa + 1 \text{ and } \kappa = {}^{-1}\!/_{N^2}.$$

Since the conic constant κ for the bounding refractive index range covers from about -0.25 to about -0.60, which represents an elliptical shape because the conic constant less than zero and greater than minus one. The geometric parameters can then computed by the following equations.

The eccentricity *e* of the elliptical shape is $e = \sqrt{-\kappa} = c/a$. Further, $a = R/p = R/(\kappa+1)$ and $b^2 = a^2 - c^2$.

For an elliptical lenticular lens array, the maximum separation, S_{max}, between the vertex of each lens element is given by

$$S_{max} = 2b = \frac{2RN}{\sqrt{N^2 - 1}}.$$

The array has a pitch defined by the number of lenticules per unit length (lpu), where the unit length could be an inch or a millimeter. For the lenticular lens array, the minimum pitch, P_{min}, is given by the following equation:

$$P_{min} = \frac{1}{2b} \text{ [lpu]}$$

For a particular application of the elliptical array, the distance y can be chosen and is one half the width of the lens element. The width of the lens element can define a field of view for the lens element on the rear surface, which can be chosen to provide a field-of-view wide enough for a desired number of interlaced images. After choosing the distance y, the x coordinate on the major axis, or sag (*d*), for the distance y can be determined using above elliptical shape equation.

The preceding discussion relates to a lenticular array having where the lenses and the body are monolithic. In many cases, print projection optics comprise a lenticular lens array, one or more base layers, and appropriate bonding materials. The refractive index of these different materials often varies somewhat. This requires modification of the thickness equation. The addition of the other materials can introduce additional aberrations, predominately spherical and coma.

The lens array and the substrate can comprise different materials, which can have different refractive indexes. Consider that the lens array can comprise a material having a refractive index of N_1 and the substrate can comprise a material having a refractive index of N_2. From basic aberration theory, the different refractive indices of the array and substrate materials can introduce additional spherical aberration. To compensate for the different refractive indices, the equation relating *R, N,* and *t* can be modified as presented in the following equation to determine the radius *R* of each lens element when the array comprises two or more different materials.

$$R = (N_1 - 1)\left(t_1/N_1 + t_2/N_2 + \ldots t_n/N_n \right).$$

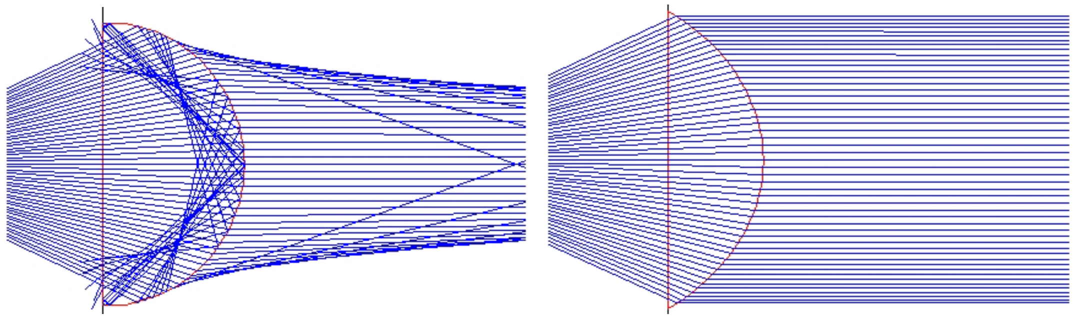
The value of the radius *R* results in the image from a distant source being formed upon the back surface of the nth substrate. This equation can apply when the lenticular lens array comprises more than one substrate. In practice, the lens element is cast and has a thickness t_1 typically slightly greater than *d*. The conic constant can be estimated by

$$-1\big/ N_{effective}^2 \text{ where } N_{effective} = t_0 \big/ (t_0 - R) \text{ and } t_0 = \sum_{i=1}^{n} t_i$$

It is also interesting to note that the so-called F-number in the medium is no less than $\frac{N}{2(N-1)}$.

[1] The distance y can be chosen based on the particular application for the array. The distance y is one half the width of the lens element. The width of the lens element can define a field of view for the lens element on the rear surface. Accordingly, the distance y can be chosen to provide a field-of-view wide enough for a desired number of interlaced images. After choosing the distance y, the x coordinate on the major axis (sag) for the distance y can be determined.

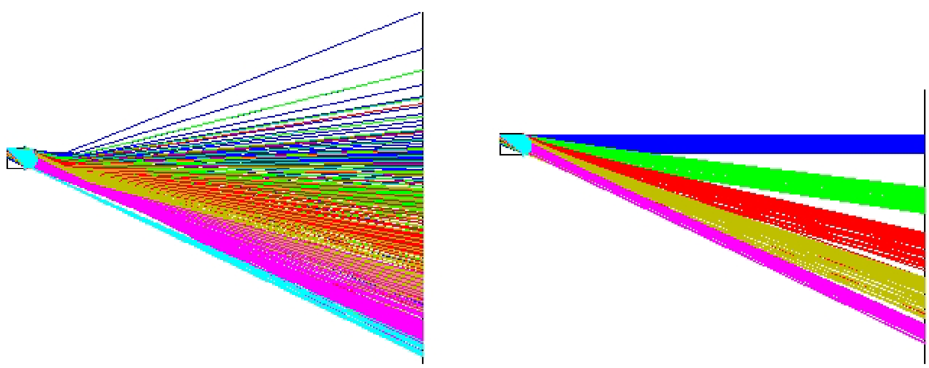
3. LENTICULAR LENS ANALYSIS



(a) (b)

Figure 4. Conventional cylindrical lens (a) shows total internal reflections and loss of aperture while elliptical lens demonstrates well-collimated rays.

ZEMAX was used to model the various lenticular lens configurations. Figure 4(a) shows that with a conventional cylindrical lens, total internal reflections can occur that limit the amount of aperture which is useful of the lenticule. This limitation causes the image to less "bright" since less light can get in and out when compared to the elliptically shaped lens illustrated in Fig. 4(b). Although the lenticule boundaries are shown, the source and the material in between the source and the lenticule have the same refractive index as the lenticule. The improvement is evident and is, in part, why the elliptical lenticule provides brighter images having higher contrast.



(a) (b)

Figure 5. Half-field beams for a cylindrical lens element (a) and an elliptical lens element with an axial source and four off-axis source.

To evaluate the off-axis performance of the different lenticules, the flat back surface of each lenticule was segmented into nine parts. Due to symmetry, only the center and the four segments on one side need to be examined. A point source was located at the center of each segment and fans of rays were then traced through the lens. Ideally, one would observe five collimated beams exiting the lenticule; however, aberrations degrade the collimation and separation. The beam direction θ is given by first-order optics to be $\tan\theta = h/f$ where h is the distance from the optical axis to the source. Figure 5(a) show the exiting beams for a cylindrical lenticule and Fig. 5(b) shows the beams for an elliptical lenticule. The improvement in beam separation is remarkable and results in observed images having less ghosting and crosstalk.

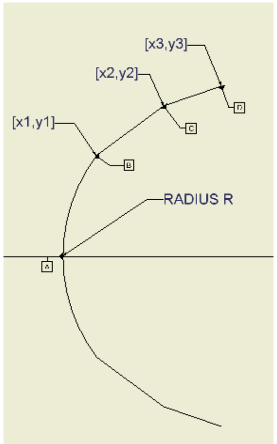


Figure 6. Pseudo-elliptical lenticule.

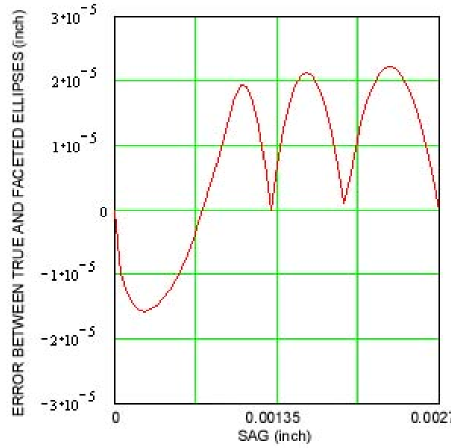
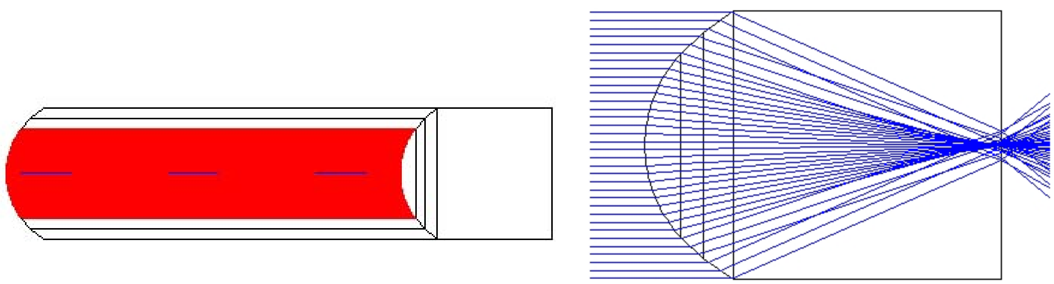


Figure 7. Sag error between a true elliptical and pseudo-elliptical (three facets) surfaces

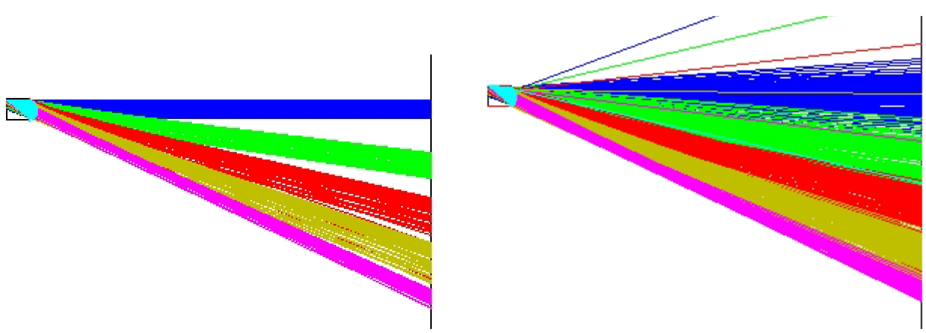
An intermediate alternative for improving the cylindrical lenticule performance was considered. The concept was to create an approximate elliptical shape using a combination of a circular vertex radius and straight-line segments (facets), or perhaps just segments. This pseudo-elliptical (or faceted) lenticule is depicted in Fig. 6 and shows the vertex radius and two segments on each side. Figure 7 shows the representative sag error between the ideal elliptical shape and the pseudo-elliptical shape for a typical size lenticule. In this case, a three-faceted and circular tip pseudo-elliptical shape yielded a worse-case fit of about 0.5 µm.



(a) (b)

Figure 8. Oblique view (a) and side view (b) of a pseudo-elliptical lenticule.

Figure 8(a) shows an oblique view of a pseudo-elliptical lenticule where the dark area is the cylindrical portion and the two facets are in white. Figure 8(b) presented a raytrace for a distant point-source object for this two-faceted lenticule. As can be observed, the image quality is degraded by spherical aberration and the non-focusing nature of the individual facets, i.e., they tend to redirect the light passing through them.



(a) (b)

Figure 9. Comparison of exiting beams from an elliptical lenticule (a) and a pseudo-elliptical lenticule (b).

Figure 9 presents a comparison of exiting beams from an elliptical lenticule (a) and a pseudo-elliptical lenticule (b) where the focal length is 0.35 mm (0.014 inch). Examination of this figure shows that the pseudo-elliptical lenticule provides reasonable good optical performance compared to the elliptical lenticule, and significantly better performance that the conventional cylindrical lenticule shown in Fig. 5(a). Also, modeling has shown that the usable field-of-view of the elliptical and pseudo-elliptical lenticules is approximately 5% greater than the conventional cylindrical lenticule.

4. TOOLING

As was mentioned previously, the lenticular material is typically formed into sheets, which may be individual sheets or a continuous roll. The material may be made as a single piece or as a sandwich of two or more layers. The image content to be projected may be printed directly onto the flat back surface of the sheet, printed on a backing material that is then bonded to the flat side of the sheet, or some other variant. The selection of method is primarily driven by the application of the resultant product, the printing technology available, and cost.

Creation of the lenticular portion of the sheet material is predominantly accomplished by using an extrusion method that was described in Section 1. The extrusion drum is a very challenging part to manufacture. These drums are very large and heavy, and have to have the lenticule pattern precisely formed thereupon. The quality of the drum strongly determines the quality of the sheet material and the resulting image projection performance. The printer can compensate for only so much and can do little if anything it is focus and/or pitch varies. Although there are several critical factors in fabricating an acceptable extrusion drum, the most critical is the fabrication of the diamond tool used to cut the groves into the drum face. The tool can be used to cut parallel groves using a plunging technique or to cut a spiral grove as a continuous cut. In either case, the lathe or diamond turning machine has to have extremely high stiffness and precision. Considering the size and weight of the drum, such a machine is not readily found in the typical machine shop or optical fabrication facility. The specific details of drum cladding material, its preparation, cutting procedures, and handling are proprietary.

Although fabrication of diamond cutting tools for single-point diamond turning is a relatively mature technology, fabrication of cutting tools having the desired elliptical shape profile is at the state-of-the-art. Single-point diamond-turning tools have a circular shape profile and are “easy” to make with very little waviness. Fabrication of elliptically shaped tools requires significantly greater skill and specialized machinery. To put it into perspective, consider the difficulty of shaping a diamond, having a width of between 2-5 human-hair diameters, to a specific elliptical profile with very small waviness. Consider further the metrology challenge to verify that the shape is correct. Neither task is simple. The pseudo-elliptical tool is actually easy to fabricate than the elliptical tool since the vertex region has a circular profile (relatively easy to make) and several flat facets on each side. Although not trivial, grinding the facets onto the tool in the correct locations and angles can be done. Tools having the elliptical and pseudo-elliptical shapes have bee fabricated and used successfully to make lenticular engraved extrusion drums.

5. CONCLUSIONS

During the past decade, products incorporating lenticular materials have grown rapidly and continue to do so. The lenticular technology research reported in this paper demonstratively shows the performance improvement of both the pseudo-elliptical and true-elliptical lenticular lens array materials over the conventional cylindrical lenticular lens array materials. This new approach also allows the manufacture of very thin gauge materials that can be used in numerous applications where flexibility and shape conformance are important.

Pseudo-elliptical and true-elliptical lenticular lens array materials can provide benefits as follows:

- A lenticular lens array that can provide optimized printed-display quality of animated and three-dimensional images for mass production.
- The lenticular lens array can mitigate the spherical aberration typically suffered by conventional lenticular arrays and further improve the off-axis image quality.
- Allows utilization of thinner gauge lenticular lenses to achieve the same or better performance of same or heavier gauge materials.

- Provides a lenticular lens array having a reduced lens junction depth, which can mitigate off-axis light blocking by adjacent lenses.
- Provides less cross talk, (image ghosting).
- Sheets of thinner lenticular lenses offer significant advantages when affixed to cylindrical objects vs. thicker lenses.
- Use of thinner lenticular gauge material reduces costs of use up to 50% percent as compared to conventional heavier lenticular gauge materials used today.
- Allows printing upon a lenticular lens array that can substantially optimize printed display quality of animated and three-dimensional images used for mass production of lenticular printed products
- Allows quality-based printing upon thinner gauge lenticular materials using “continuous” web fed roll print production technology vs. “one at a time”, single sheet-fed print production.
- “Continuous” web fed roll print production is much more cost efficient than “one at a time”, single sheet fed print production

Combining the aforementioned mentioned technologies can create new, never-seen-before printed lenticular formats and structures including: entire outer lenticular packaging enhancements (box over wraps); segmented applied lenticular label coverage to outer packaging; pressure sensitive, non-pressure sensitive, self adhesive, and non-self-adhesive lenticular label products; multi-ply, multi-substrate peel open pressure sensitive and non-pressure sensitive lenticular labels; lenticular laminated to paper board products; packaging in-packs and on-packs; beverage cups having decorative partial or full lenticular cup wraps; video, dvd, or cd disc cover lenticular treatments; direct mail; magazine inserts; newspaper inserts; or contest and game sweepstakes components that comprise use of partial or full lenticular enhancements.

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