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Abstract. A brief history of recent developments in electronic stereoscopic displays is given concentrating on products that have succeeded in the market place and hence have had a significant influence on future implementations. The concentration is on plano-stereoscopic (two-view) technology because it is now the dominant display modality in the marketplace. Stereoscopic displays were created for the motion picture industry a century ago, and this technology influenced the development of products for science and industry, which in turn influenced product development for entertainment. *© 2012 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.OE.51.2.021103]

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Elsewhere in this issue, Vivian Walworth describes the early days of the stereoscopic display medium and its nascent industrial development, especially with regard to polarization as a technique for image selection and the Polaroid Corporation's inestimable contribution. The recording media used was conventional silver halide photography, and great progress was made by workers in the field in perfecting the art of stereoscopic capture and display, including projection, using techniques that remain important, such as image selection by means of circular polarization. The recent growing commercial interest in stereoscopic imaging for entertainment is directly linked to electronic displays and digital technology. It is my intention to briefly recap electronic stereoscopic display technology's progress during the past three decades.

For stereoscopic displays, as is the case for most engineering and scientific disciplines, progress is usually incremental and advances are dependent on prior art developed by workers who, in turn, also owe a debt of gratitude to those who came before them. This is the case for today's electronic stereoscopic displays and related technology. The precursors of modern stereoscopic displays can be found in earlier work using conventional motion picture projectors modified to perform the task of projecting a stereoscopic image on a theater screen. The most relevant work containing seeds that have flowered into modern products is the Teleview system (Fig. 1). It was created by Laurens Hammond, later to invent the eponymous organ, and introduced at the Selwyn Theatre in Manhattan at the end of 1922. Hammond's precocious device is similar to others described in the patent literature in the decade prior to his commercial exhibition, but his device is important because it is the only one like it seen by paying customers. It used eclipse technology—this term refers to occlusion of successive images in which the images are temporally multiplexed and projected on a screen and then directed to the left and right eyes by means of mechanical shutters. Hammond used interlocked 35 mm projectors with lorgnettes with spinning mechanical shutters for image selection mounted on the back of every seat in the theater, with the lorgnettes' and projectors' shutters kept in sync by synchronous AC motors.

The mechanical advancement of a motion picture frame takes a relatively long time, whereas certain electronic displays refresh rapidly with only a small interval between frames. This observation was the key to understanding why a single digital projector, using the Texas Instruments digital light processing (DLP) micro-mechanical mirror light engine, is capable of projecting field-sequential stereoscopic images. Although the results on the screen, in terms of the rapid alternation between left and right frames is the same, in concept, as Hammond's, a single digital projector with suitable selection device technology can take the place of two film projectors. It is this that makes the modern stereoscopic cinema practical in combination with electro-optical shutters and modulators, which are the key ingredients in most stereoscopic displays.

In the late 1970s and early 1980s, Honeywell and John Roese (at the Naval Ocean Systems Center in San Diego) independently demonstrated flickering field-sequential displays using electro-optical shutters made of lead lanthanum zirconate titanate (PLZT) shutters. These displays were dim, slow, buzzing devices with visible embedded electrodes to power them that required the application of a few hundred volts and were positioned only a few millimeters from the eyes. By today's standards, this seems like a bad dream, yet they were all we had at that time—I still have one in its little plastic case with its Motorola label somewhere in my desk. They were used in conjunction with field-sequential stereoscopic images displayed on cathode ray tube (CRT) monitors. The images flickered because the refresh rate was low based on a standard video field rate of 60 Hz. Thus, each eye saw only 30 fields per second when looking through the shuttering devices. In 1981, my colleagues and I at StereoGraphics Corp. were using these PLZT shutters mounted in welder's visors and hit upon the now obvious idea of upping the field rate to 120 Hz. In order to do that, we came up with a solution that allowed us to modify off-the-shelf cameras and monitors to run at 120 Hz and demonstrated that a single display, a black-and-white Conrac CRT monitor, could show a flickerless stereoscopic image. This was a milestone little noted at the time, but it is the technological basis for much of the current industry's products for motion picture projection and home television.

The quest at StereoGraphics and another interested organization, Tektronix, was to improve the electro-optical shutters. The obvious choice in the early 1980s was to use a liquid crystal technology of the twisted nematic (TN) type, but these parts were too slow. StereoGraphics developed a faster liquid crystal technology, which we licensed from James Fergason, who with his associate, Arthur Berman, helped us to meet our specification (Fig. 2). Fergason, a renowned inventor in the field, had devised what he called the surface mode (SM) device, which has become better known as the π-cell. The π-cell shutter was fast enough (i.e., the transition from opened to closed and vice versa), but its extinction was too low; it had a dynamic range of only 15 to 1, and we needed an order of magnitude improvement to suppress ghost images caused by cross-talk. We tried putting two together in optical series (also using TN parts) to improve the dynamic range, and it worked well enough when mounted in modified headband magnifiers originally intended for model makers. The head-band unit was plugged into a controller that powered the low-voltage shutters and kept them in sync with the video field rate. This resulted in a decently bright, flicker-free 120-Hz stereo image. Most of our early customers in the mid-1980s were looking at computer-generated images, but we knew that we had to eliminate the controller and its tethering cable to expand the market for electronic stereoscopic displays.

We realized that having two shutters in an optical series was a nonstarter for wireless eyewear because of weight and power consumption. To eliminate the tether meant using batteries and lightweight, low-powered shutters. Indications of how such a device might be configured can be found in the patent literature. In particular, a concept by Karl Hope from the 1970s showed active eyewear linked to a video source by means of radio using shutters made up of fixed gratings and motor driven reciprocating gratings. We wound up using an infrared link and liquid crystal shutters, but Hope pointed the way.

To improve on the performance of the SM devices, we embarked on a program of experimentation that lasted two years. The liquid crystal cell itself was sandwiched between two linear polarizers whose axes were orthogonal. We hit upon the now widely used optical compensation technique (adding a retarder between one of the polarizers and the cell) in what may well have been its first commercial application to improve the dynamic range of the π-cells. While TN parts used the physics of optical activity, the π-cell devices used the physics of phase shifting. They were faster than the TN parts because the bulk of the liquid crystal material was not involved in their transition of states. As the name *surface mode* implies, the directors immediately adjacent to the electrode surfaces and director alignment layers were primarily responsible for the phase shifting. Since less material was involved in the transition than the TN devices, which involved the movement of all of the directors or bulk, as it is called, the SM devices were faster.

However, the unadorned SM shutter's first polarizer in combination with the cell itself produced elliptically polarized light that was best analyzed with an elliptical analyzer—the combination of retarder and second polarizer. The new parts had a dynamic range of 800 to 1 and became the heart of CrystalEyes, introduced in 1989, the first wireless active eyewear. We sold about 150,000 of this product to scientists and engineers in the course of two decades. Several years after its introduction, we switched to lower cost Super Twisted TN parts devised by Mary Tilton. Modern variations, in form and function, for viewing motion pictures and television, closely resemble CrystalEyes. A model I recently saw from Samsung uses plastic liquid crystal shutters, resulting in a substantial improvement in form factor and reduction in weight.

We also knew there were two possible configurations for selection devices for viewing stereoscopic images on CRT monitors—shuttering eyewear or on-screen polarizing modulators in conjunction with polarizing eyewear. We worked on both, and Tektronix specialized in the on-screen modulator, which used a linear polarizer on the monitor side that was laminated to a π-cell with a quarter-wave retarder that was laminated to the viewer surface to produce circularly polarized light. Alternatively, a circular polarizer could be laminated to the π-cell, which was the part facing the CRT monitor. The device was electrically driven to switch between left- and right-handed circular polarization, and when viewed with analyzing spectacles, the system allowed for more head tipping than linear polarization image selection. One could look at the system as either a shutter with distributed parts or as selection by polarization.

Tektronix did a good job seeding the market in the mid- to late 1980s by placing units at universities and in research laboratories. Typically, their modulator was bundled with their branded monitors. The Tektronix version used what was called a Byatt shutter, namely a π-cell made up of rows of independently driven sections that are energized in synchrony with the scanning of the CRT's electron beam's writing of the image. This had the advantage of vastly reducing cross-talk by turning the light that would have contributed to cross-talk into a useful image.

StereoGraphics concentrated on the push-pull version of the modulator using two π-cells in optical series electrically driven out of phase. A linear polarizer was laminated to the first inward facing surface, and when the parts were driven as described, the vector sum of the output was the sequential production of left- and right-handed circularly polarized light. Such a modulator has symmetrical characteristics for left and right fields and fast transition times (0.5 ms) and could be tuned to have fairly clean circular polarization. However, it had certain limitations, one of which was that the increased optical path length reduced the angle of view of the device, making it less than ideal for monitor applications. The cells were big and expensive parts, so two of them substantially increased the cost. But while these issues were a limitation for a monitor, they were not a limitation when the device, which we dubbed the ZScreen (for the third dimension), was placed in front of a projection lens with the relatively restricted angle of view of the projection beam. The ZScreen was the basis for the first commercially successful modern stereoscopic theatrical cinema system.

Remarkably, whatever the aforementioned limitations of the ZScreen and the relative size and sophistication of the companies involved, StereoGraphics prevailed over Tektronix in a major procurement, our first original equipment manufacturer (OEM) deal, and we sold hundreds of these modulators to Evans & Sutherland, which at that time had a robust molecular modeling workstation business. Years later, StereoGraphics reintroduced an improved version of

Fig. 1 Hammond's Teleview system. Only one theater in Manhattan was so equipped. Each seat in the house had attached to its back a gooseneck-mounted spinning mechanical shutter which was run in synchrony with the projector shutters. This is the precursor of all field-sequential movie and TV displays which are the great majority of products on the market.

the single-cell modulator and sold thousands of units into the field of aerial mapping. At recent trade shows, both Samsung and LG have exhibited three-dimensional (3-D) TVs using what I believe to be single-cell Byatt modulators, and Samsung has also made a product announcement in this area.

Silicon Graphics, a rising star in the business of computer graphics workstations, saw an opportunity to enter the field of molecular modeling, in which stereoscopic viewing was *de rigueur*, and they requested that StereoGraphics supply them with a wireless shuttering eyewear solution. We were happy to do so since we were far along such a development path; within six months of their request, we delivered CrystalEyes, which was introduced in 1989 at Siggraph (Fig. 3). Silicon Graphics adopted it as their own branded product, and after the release of CrystalEyes, Evans & Sutherland also adopted the solution. CrystalEyes had better image quality and cost a lot less than the on-screen modulator. For decades, products originated by Tektronix and StereoGraphics filled a need for 3-D workstation visualization in fields like oil and gas exploration, computer-aided design for autos and heavy equipment, molecular modeling, public and private sector use of aerial mapping, medical imaging, and in some relatively esoteric engineering and scientific fields such as computational fluid dynamics and modeling of currency trading. Remarkably, from time to time we had requests from psychologists who wanted to use CrystalEyes for testing primate perception. We called those units *monkeyware*.

StereoGraphics developed a ZScreen for use with CRT projectors that allowed for the viewing of stereoscopic images with circular polarizing spectacles (Fig. 4). The image was projected on a polarization conserving screen. CrystalEyes eyewear was also sold into projection applications for presentations and collaborative work efforts. I was present at one such session at the General Motors (GM) design center when then chairman, Roger Smith, and members of the GM board used CrystalEyes to view new Chevy models projected on a large triptych screen using Barco projectors. Being able to visualize designs this way cut significant time off the product development cycle, and I was told that the ability to reproduce glitter and luster as reflected by the auto bodies, different for each eye, was as important to GM as the 3-D effect.

A milestone in projection technology, leading the way to today's stereoscopic cinema, was Texas Instruments' DLP projection technology. It is especially well suited to field-sequential stereoscopic projection because it contributes no cross-talk to image selection, resulting in a clean, ghost-free image. In the early days of the 21st century, the ZScreen, in combination with projectors using this light engine from companies like Christie and Barco, while initially used for engineering and scientific applications, demonstrated the efficacy of the 3-D cinema. StereoGraphics licensed the ZScreen technology to RealD in 2003, and the company was acquired by RealD the following year. RealD has continued to develop some of the core StereoGraphics technology, such as the side-by-side multiplexing system used for television signal transmission.

Fig. 2 Jim Fergason (left) and Art Berman working at StereoGraphics on what would become the ZScreen.

In the late 1990s and early 2000s, Philips led the way in autostereoscopic development using key insights of one of its researchers, Cees van Berkel. Van Berkel ingeniously used slanted lenticules, eliminating optical moiré patterns, to cover a flat panel to produce glasses-free viewing of 3-D images, and this work pointed the way to future developments. Lenticular stereoscopic images had been used for decades for portraiture and advertising, and it was now being adapted to electronic displays. That had to wait for the flat panel display to become a viable product. A major setback in the field occurred when, a few years ago, after intensive development, Philips gave up on autostereoscopic displays, citing the economic downturn. Their work had

Fig. 3 CrystalEyes eyewear and IR emitter. Introduced for science and industry in 1989 it is the first shuttering eyewear product millions of which are now in use in theaters and homes.

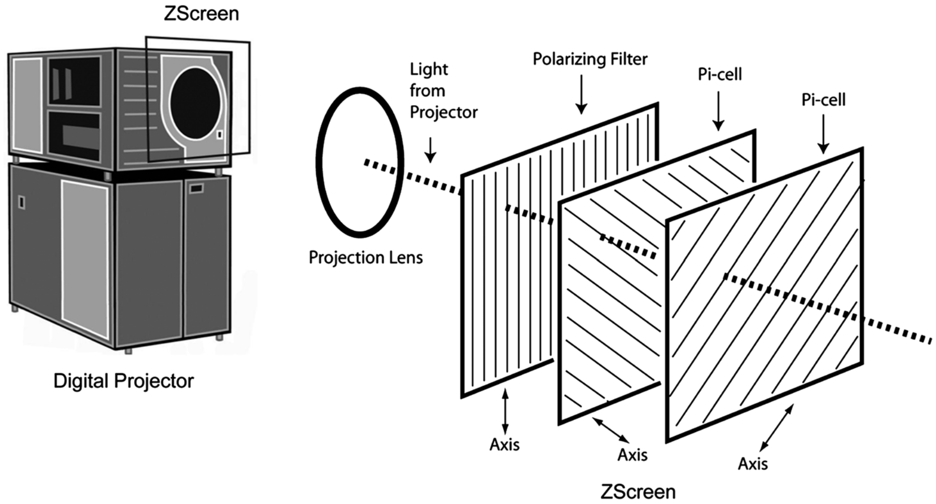

Fig. 4 The push-pull modulator. The left and right fields from a digital projector's lens pass through the ZScreen which consists of a sheet polarizer and two pi-cells. The pi-cell axes are orthogonal to each other and at 45 degrees to the polarizer axis. The pi-cells are switched on and off out of phase with each other with the result that successive fields are alternately left and right handedly polarized.

concentrated on improving lenticular optics, finding means to transmit and display multiview information, and synthesizing depth information from planar images.

At StereoGraphics, we spent a number of years on and off, beginning in 1981, trying to develop autostereoscopic displays. But no progress could be made until flat panels were available because of the requirement to have the selection device, in this case a lenticular sheet, in both tight tolerance alignment and intimate juxtaposition with the underlying pixels. In the first years of the 21st century, we developed our own technology and sold over 100 evaluation units that honestly were not ready for prime time. Philips hit upon the ingenious concept of transmitting a planar image along with a depth map, and eventually additional information, to reconstruct at the TV set or monitor the necessary number of views required by an autostereoscopic display panel. While a stereoscopic display requires only two views, an autostereoscopic display with a wide viewing angle requires many views.

To give the reader an idea of what is required, a planar television set can be viewed over a 180-deg horizontal field, but obviously, the extreme off-axial areas are then undesirably distorted. So the useful viewing angle must be restricted to 100 deg. As a rule of thumb, for an autostereoscopic display, each horizontal degree in space in front of the monitor requires its own view. In order to make a 100-deg single viewing zone autostereoscopic display with a high-definition 1920×1080 image in each view, we require 100 such images at the display surface. That is a lot of pixels and is the problem to solve without regard to specific selection technology. As a wise physicist once said, "You cannot fool Mother Nature"; if we want to have a wide-angle, single–viewing zone autostereoscopic display, one way or another, a gigantic number pixels must be made available for the eyes. The problem, as always, is the opportunity, and I have no doubt that this will eventually be solved. When and how are the unanswerable questions.

Just as a color television at home drove the introduction of color for computer monitors, it is my belief that the entertainment applications of stereoscopic displays are motivating the adoption of stereoscopic display technology for scientists, engineers, and artists. There is now a strong commercial motivation to improve stereoscopic technology. A point not to overlook is that while this technology has been costly in the past, anybody can now head down to Best Buy and buy a good stereoscopic monitor (or camera!) and eyewear at consumer prices. Portable single-user devices, laptops, tablets, and phones are a promising additional application for stereoscopic displays since they have begun to use interdigitated stereopairs viewable by means of a raster barrier or similar technology. Since the user is able to guide herself or himself to the *sweet spot*, the problem described above, with regard to the requirement for a great many views, is a non-issue. To my eye, many of these displays are good and have a great deal of charm.

The eclectic collection of articles in this journal serves as proof of the great interest in stereoscopic technology. Binocular stereopsis may have been favored by evolution to help us with our skills as predators, but it has had the effect of turning us into master technologists. This depth sense is intimately related to our ability to visualize and manipulate our world and has made a major contribution to human intelligence. It is my hope that work in the field continues to produce such benefits for mankind.

Acknowledgments

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Lenny Lipton founded StereoGraphics Corporation in 1980 and was the CTO of RealD from 2005 to 2009. He has been granted 50 patents in the field of electronic stereoscopic displays with approximately 50 more pending. In 1996, he received a Smithsonian award for the invention of CrystalEyes, the first shuttering eyewear product for stereoscopic displays. He led the team that invented the ZScreen, used in thousands of theaters, and he created the first flicker-free, field-sequential, 3D display technology and the primary multiplexing techniques used for many stereoscopic cinema and TV products. He has written four books, including *Independent Filmmaking* (1972) and *Foundations of the Stereoscopic Cinema* (1982). He is a fellow of the SMPTE and SPIE. He is also a member of the Board of Directors Executive Committee of the International 3D Society and a recipient of their Lifetime Achievement Award. As an undergraduate at Cornell, he wrote *Puff the Magic Dragon*. He and his family live in Laurel Canyon, California.