Emerging Digital Micromirror Device (DMD) Applications

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ABSTRACT

For the past six years, Digital Light Processing™ technology from Texas Instruments has made significant inroads in the projection display market. With products enabling the world's smallest data and video projectors, HDTVs, and digital cinema, DLP™ technology is extremely powerful and flexible. At the heart of these display solutions is Texas Instruments Digital Micromirror Device (DMD), a semiconductor-based "light switch" array of thousands of individually addressable, tiltable, mirror-pixels. With success of the DMD as a spatial light modulator for projector applications, dozens of new applications are now being enabled by general-use DMD products that are recently available to developers. The same light switching speed and "on-off" (contrast) ratio that have resulted in superior projector performance, along with the capability of operation outside the visible spectrum, make the DMD very attractive for many applications, including volumetric display, holographic data storage, lithography, scientific instrumentation, and medical imaging. This paper presents an overview of past and future DMD performance in the context of new DMD applications, cites several examples of emerging products, and describes the DMD components and tools now available to developers.

INTRODUCTION

Texas Instruments began working on a spatial light modulating technology nearly twenty-five years ago. Starting as the Deformable Mirror Device in 1977, the technology evolved to a bi-stable, or Digital Micromirror Device in 1987. Over the next decade the DMD technology was perfected, and with the necessary support electronics, was commercialized in the form of Digital Light Processing™ technology in the spring of 1996. As of October 2002, over 1.5 million systems have been shipped into the projection display marketplace, making DLP™ the most widely adopted reflective light modulator technology.

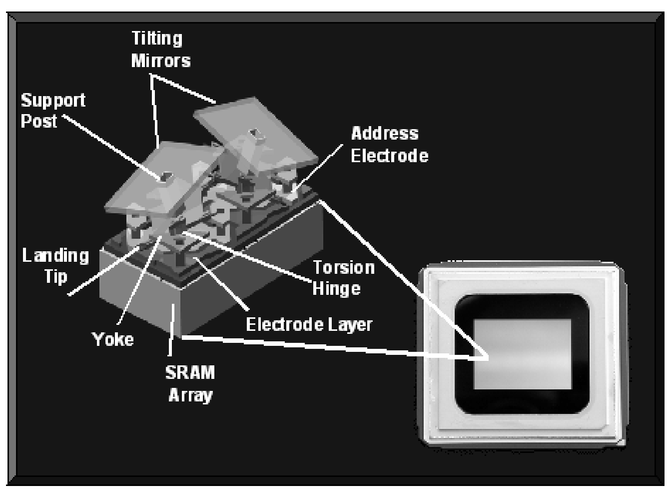

Figure 1. Schematic of two DMD mirror-pixels next to a typical DMD light modulator consisting of 1024 x 768 individually addressable mirror-pixels.

The DMD is the only volume production device that is both a micro-electronic mechanical system (MEMS) and a spatial light modulator (SLM). It is a MEMS because it consists of hundreds of thousands of moving micromirrors that are controlled by underlying CMOS electronics as shown in Figure 1. The mirrors are highly reflective and used to modulate light, thus making the DMD an optical MEMS (MOEMS) as well as an SLM, and more specifically a reflective SLM. Liquid crystal devices (LCDs) are also widely-used SLMs and may be either transmissive or reflective, binary or analog, but do not have the speed, precision, or broadband capability that makes the DMD so attractive for many applications.

MODULATING LIGHT FOR DISPLAY APPLICATIONS

For the most advanced DMD today, the mirrors are made to rotate to either a +12 degree or –12 degree position depending on the binary state of the SRAM cell that exists below each mirror. The SRAM voltage is applied to the address electrodes, creating an electro-static attraction. When a voltage pulse is applied to the mirrors, each mirror then either stays in place or quickly rotates to its opposite state according to the SRAM data. Once stabilized, the mirror may be considered electro-mechanically "latched" in its desired position, and the state of the SRAM cell may then be changed without affecting the state of the mirror.

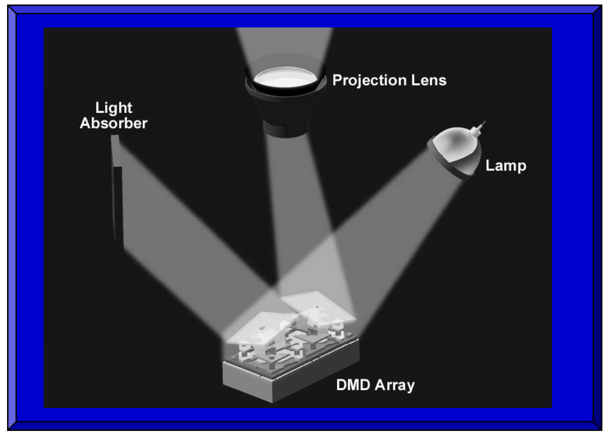

Figure 2. Two mirror-pixels. One mirror-pixel is turned "on" and reflects incoming light through a projection lens to the screen. One mirror-pixel turned "off" reflecting the light away from the lens.

Using a typical metal-halide or mercury arc lamp as a light source, each tiltable mirror-pixel can be moved to reflect light to, or away from, an intended target (Figure 2). In projection systems, brightness and contrast are two primary attributes that impact the quality of the projected image. The DMD has a light modulator efficiency in the range of 65%, including mirror reflectivity, fill factor, diffraction efficiency and duty cycle, and enables 1000:1 typical contrast ratio at the system level, or as high as 2000:1 for slower optical systems.

In addition to being highly efficient, the speed at which each mirror can modulate between the "on" and 'off" states is another key DLP™ advantage. Fast switching speed has enabled a compelling range of end products including the world's smallest video and data projectors, HDTVs, and digital cinema. In the case of projectors, the microsecond speed allows the use of only one DMD light modulator resulting in small, compact optical architectures (Figure 3), and thus very small projectors. Competitive approaches using slower modulators require three separate modulators for independently modulating red, blue and green sources. For digital cinema (using three DMDs, one for each primary color), the fast switching enables over 14-bits of grayscale per color, producing images that meet or exceed the quality of film.

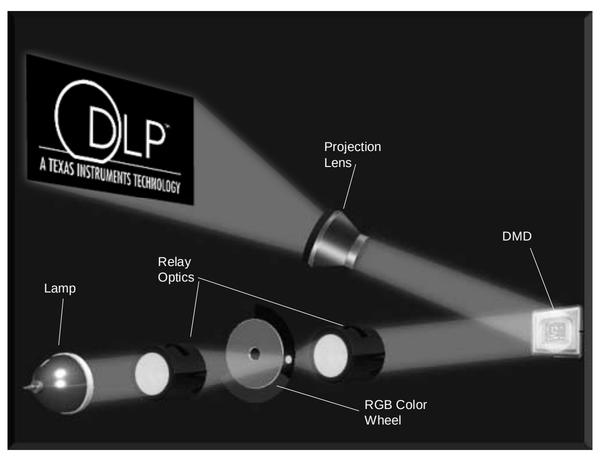

Figure 3. A one-chip DLP™ projection system. White light is focused down onto a spinning color wheel filter system. The wheel spins illuminating the DMD sequentially with red, green, and blue light. At the same time RGB video signal is being sent to the DMD mirror-pixels. The mirrors are turned on depending on how much of each color is needed. The eye integrates the sequential images and a full color image is seen.

BINARY PULSE WIDTH MODULATION (PWM)

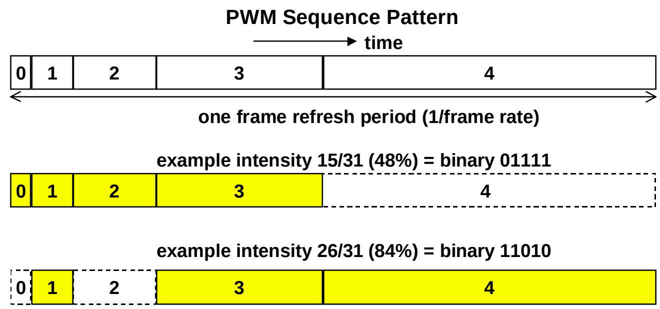

Figure 4. Binary PWM sequence pattern with two examples of how intensity values are generated for 5-bit video

Light intensities from the DMD are produced by pulse width modulating the mirrors over the operating refresh time. For projector products, standard video signals are converted to this PWM format by DMD supporting electronics. In the binary PWM pixel representation in Figure 4, a pixel's LSB consumes $1/(2^n-1)$ of the total refresh period, where n is the number of bits per color. The LSB+1 bit consumes double the LSB time. This pattern continues for all bits of the given pixel. The human visual system effectively integrates the pulsed light to form the perception of desired intensity. The gray scale perceived is proportional to the percentage of time the mirror is "on" during the refresh time.

ENABLING EMERGING APPLICATIONS

As the DLP™ projector technology was becoming mature, TI experienced considerable interest from engineering and scientific communities in using the DMD for different applications addressing a broad variety of markets. During that time TI elected to focus on the projector markets and not to dilute its resources on new applications. Now that significant projector market share and resulting business success have been achieved, TI now seeks to enable non-projector applications and products.

In order to maximally address the wide variety of new opportunities, a line of flexible products has been created and made broadly available to system developers through value-added resellers. This DMD Discovery™ product family features the 0.7 XGA DMD that began production shipments for projector applications in 2002.

For projector applications the DMD chipset includes a digital formatter that converts standard video and graphics data formats into spectacular screen images. However, this highly specialized formatter has proved to be too cumbersome for new applications that may have unique data formats and may desire to project binary images instead of those of varying color hue and intensity. To address this need for flexibility, the DMD Discovery™ family therefore features a flexible controller allowing system developers to define their own data formats and mirror timing.

BINARY AND GRAYSCALE FRAME RATE CAPABILITY

With the flexible controller, a wide range of frame rates and intensity depth can be achieved. Figure 5 describes the maximum achievable frame rate as a function of PWM bits that can be displayed within one frame. The 0.7 XGA DDR DMD is organized into 16 mirror sections, allowing each mirror section to be latched independently (1). This enables an LSB bit plane shorter than the ~100us full array load time while still maximizing "expose" duty cycle and brightness. In this phased reset mode the minimum LSB period is determined by the mirror transition and settle time (about 18us as shown in Figure 6) plus the time required to reload the mirror section with new data (about 6us). For binary (black-and-white only, no gray) operation the LSB is equal to full array load time (~100us) unless partial array operation is used. Binary frame rates up to 9,700 and 40,000 frames /second can be achieved for full array (1024x768) and partial array (<190 rows) operation, respectively. Note that advanced techniques are typically used in DLP™ projector products to create shorter expose times than the ~24us described above, resulting in increased bits/frame, but with slightly reduced duty cycle and brightness.

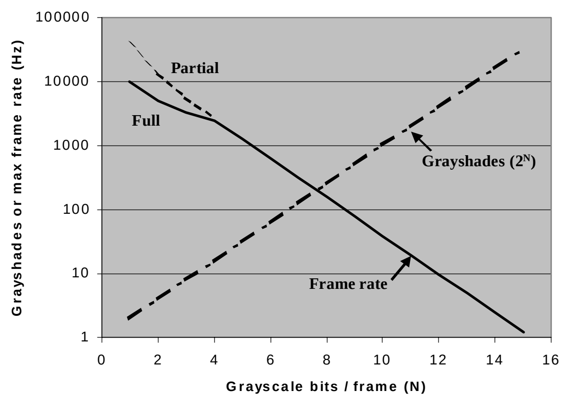

Figure 5. Maximum frame rate as a function of digital bits and resulting intensity levels (grayshades) possible within one frame time for the 0.7 XGA DDR DMD using the Discovery 1000 digital controller.

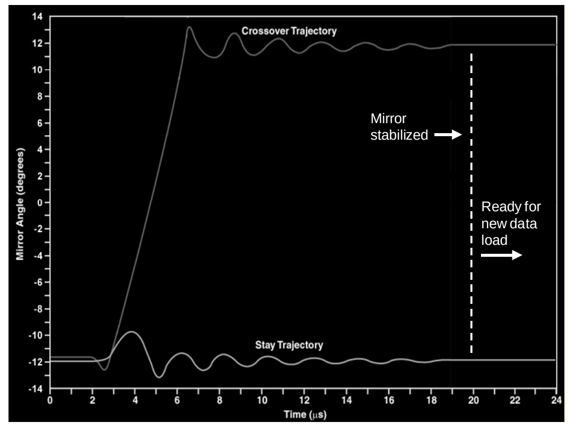

Figure 6. Mirror trajectory for both "same state" and "state transition" mirrors.

PHOTOFINISHING

The earliest DLP™ application to emerge beyond display was digital photofinishing, in which conventional film-based equipment is replaced by DMD-based opto-electronics. DLP™ index print products were introduced in 1999 that step-print a group of color photos on a single page for identification. Mini-lab products soon followed, for which the DMD in scanned mode enables continuous printing at >300 full color dpi in the process direction. This allows the production of Advanced Photo System panoramic formats under electronic control without changes to the optical system. Other advantages are image clarity due to the high resolution, excellent fill-factor, and discrete spot size. These products feature >12 bits of dynamic exposure range, and produce print quality acknowledged by experts. A DMD-based central lab configuration has recently been demonstrated that produces 4x6 digital color prints at the rate of 10,000/hr.

VOLUMETRIC DISPLAY

One of the emerging new DMD applications is volumetric display, in which DMDs are used to render 3-dimensional images that appear to float in space without the use of encumbering stereo glasses or headsets. Unlike most stereoscopic and parallax displays (such as lenticular displays), volumetric displays maintain the normal relationship between eye focusing and convergence to produce a more comfortable and realistic 3D viewing experience. They also provide both horizontal and vertical parallax—allowing the viewer to look around foreground objects to reveal previously obstructed background objects. The 3D images can be viewed from any distance over a wide field of view by a large number of viewers, each with the appropriate perspective—making collaborative efforts possible.

The Perspecta® product from Actuality Systems creates 10" diameter 3D imagery within a transparent sphere (Figure 7), that allows observers to walk around an interactive 3D image to achieve a 360^{o} perspective. Three DMDs, one for each primary color, project binary color images onto a rotating screen, creating over 100 million voxels (3D pixels), each with 8-color capability. The upcoming Z 20|20™ product from VIZTA^{3D} is a 19.5" computer graphics display (Figure 7) with a 3-DMD system projecting 2D images sequentially on 20 back-to-back liquid crystal panels. The result is the world's first solid-state volumetric display featuring 15.3 million voxels and 5 bits of grayscale per primary color. A full-on/full-off contrast ratio of over 1000:1 is expected.

Figure 7. Actuality Systems Perspecta® (left) and VIZTA^{3D} Z 20|20™ (right) volumetric displays. Both use 3 DMDs to create 3D images viewed without glasses or headsets.

LITHOGRAPHY APPLICATIONS

Lithographic applications such as print setting, PCB manufacturing, and semiconductor patterning have historically utilized materials and processes based on pattern exposure to ultraviolet light. While the pattern mask has traditionally been provided via film or photomasks, all these industries desire the ability to pattern directly from a digital file. For some markets, scanned laser systems operating at visible wavelengths are being used to satisfy this direct write need. However, most industries desire a direct write means compatible with the UV-sensitive materials and processes that have been developed over many years. Its simple reflective properties, allowing efficient modulation across a broad spectral band, coupled with its superior data rate, make the DMD an ideal device for next generation lithographic systems.

BasysPrint GmbH currently offers a line of UV-Setter™ print-setting products utilizing a standard DMD in an x-y stepped, flatbed configuration, modulating 350-450nm lamp light. The most advanced single-head system is currently able to expose ~10 million dots/sec using conventional aluminum plates that are roughly half the cost of special plates used for laser systems. In the near future DMD-based print-setting systems, including that recently demonstrated by Purup-Eskofot Dicon, will be scanned in one dimension for increased speed and reduced cost. As DMDs optimized for 350-450nm use become available, expose speeds are projected to exceed those of laser-based systems.

There are several other lithographic applications being pursued by various developers, all desiring optimized DMD operation below 400nm. A very interesting one uses the DMD to pattern custom DNA chips (Figure 8) used in drug discovery and other applications, allowing rapid iteration of biotech experimentation. Universities such as the University of Texas Southwestern Medical Center began work in this area, and companies such as NimbleGen are creating business based on this application.

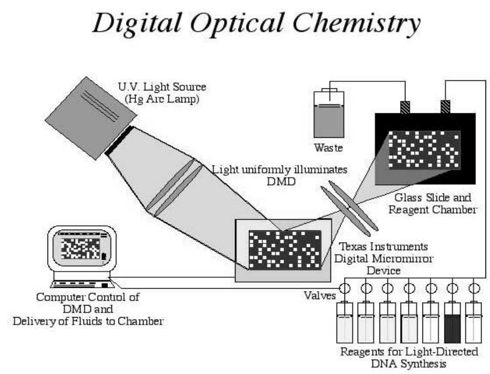

Figure 8. Custom biotech chip fabrication using a UV-capable DMD to pattern DNA sequences.

BROADBAND OPERATION

One of the inherent DMD advantages is its broadband capability. Due to its simple reflective operation, it can be made to modulate light somewhat independently of wavelength. This section deals with issues relating to DMD operation outside the 400-700nm visible spectrum.

Several years ago TI engineers recognized a tendency for DMD pixel failures after exposure to increased amounts of illumination below 400nm (2). DMDs used in projector applications therefore incorporate optical window coatings that limit transmission below this wavelength as shown in Figure 9. Projector customers provide additional filtering to limit incident flux below 400nm to <0.7 watts/cm^2. Since that time more has been learned about the root cause of these ultraviolet (UV) failures, and a 0.7 XGA DDR DMD

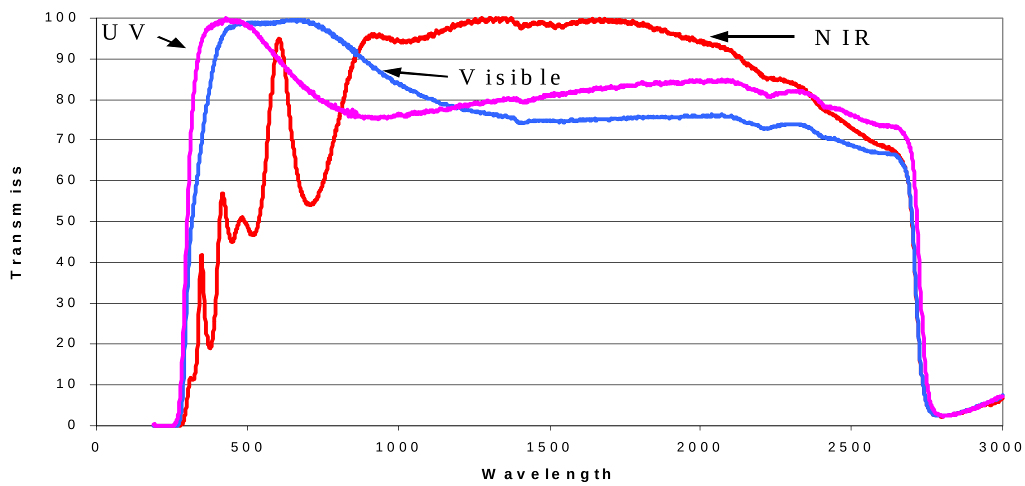

Figure 9. Single-pass transmission for DMD windows optimized for standard visible, near ultraviolet, and near infrared operation.

optimized for 350-450nm is currently under development. The near term goal is to maximize window transmission (Figure 9) and to consistently provide at least 2000 hours of useful life up to 10 watts/cm^2 at these wavelengths.

Some applications, such as semiconductor lithography, require DMD operation below 350nm. DMDs are currently manufactured using glass that has negligible transmission below 350nm. The DMD package is hermetically sealed using a proprietary process for which window materials are critical. For this reason, there is no near term plan to modify the DMD package glass. DMD products addressing deep UV applications are therefore not considered viable at this time, although advanced packaging configurations could conceivably enable this sometime in the future.

Opportunities that require transmission in the near infrared (NIR) spectrum, such as telecommunications and spectroscopy have recently emerged. DMDs optimized for 1-2um use are therefore being made available and are undergoing reliability testing. Process changes include window transmission (Figure 9) and, for telecom applications, tilt angle optimization to maximize diffraction efficiency at 1.55um Far infrared systems (>2.5nm) are not considered viable at this time due to DMD window transmission cutoff and increased diffraction issue.

DIFFRACTIVE PROPERTIES AND TELECOM APPLICATIONS

DMD diffractive issues are minimal for wavelengths below 1um in combination with fast optical systems. For longer wavelengths, the diffractive behavior of the DMD is evident for both coherent and incoherent sources, but is more obvious in coherent monochromatic sources due to the discrete well-resolved diffractive peaks observed in its reflective power distribution (Figure 10). For the standard 0.7 XGA DMD with 19.3um mirror diagonal periodicity and 12^{o} tilt angle, angular distance between diffractive peaks is approximately 3λ degrees, where λ is the wavelength in microns. In many optical systems, it is possible to collect light over a sufficiently large solid angle that a large number of diffractive orders are collected, even at wavelengths >1um. However, telecom applications that use near infrared (NIR) wavelengths coupled into fiber optical systems can be quite challenging, which is why TI has developed dedicated DMD products optimized for telecom use (3). For these applications DMDs with +/-9.2 degree mirror tilt are used to create a switched blaze grating (SBG) for which 88% of the diffracted energy is coupled into a single diffractive order. TI is partnering with OEMs to bring to market SBG-based products that leverage the speed advantages of DMD in a wide range of telecom dynamic filtering applications.

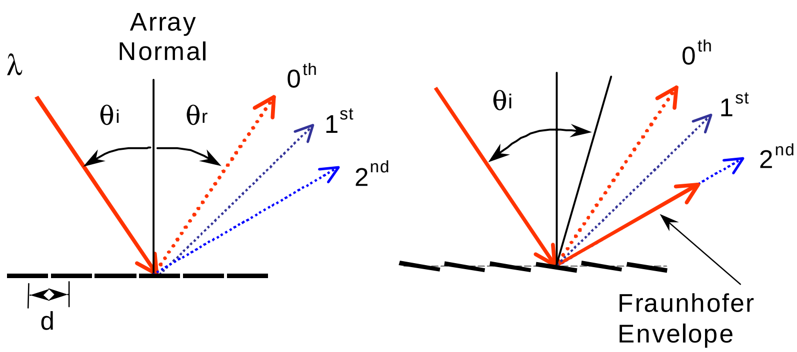

Figure 10. Incident light hitting a grating (DMD) with periodicity d with mirrors in flat state (on left) versus mirrors in +1 state (on right). In the "blazed" grating condition (on right), most of the diffracted radiation is concentrated in the 2nd order, producing a highly efficient coherent light modulator.

HIGH INTENSITY AND LASER OPERATION

With the emphasis on projector applications that require many tens of thousands of DMD operating hours, there have been no significant efforts by TI to determine maximum power levels acceptable for short term

DMD operation. DMDs routinely experience around $10W/cm^2$ of incident power between 420-700nm in the brightest DLP™ projectors. This power density is not considered a maximum, but at these levels device cooling is generally required to keep the DMD below the 65C suggested operating maximum, and to maintain package thermal gradients below a few degrees. An optical aperture is generally used to limit incident flux to the highly reflective mirror array and away from absorbing areas beyond the mirror array.

Although there has been little known effort to date in evaluating DMD operation under laser illumination, there is interest in the development community in hi-intensity laser use for manufacturing applications such as sculpting and engraving. The same thermal issues stated above for incoherent illumination are of primary consideration for continuous wave laser systems. For pulsed laser applications, keeping incident pulse energy below 0.1J/cm2 (for example 10 MW/cm^2 for 10ns) is suggested. Higher energy may cause mirror damage.

HOLOGRAPHY AND DATA STORAGE

As a technique to numerically record and reconstruct entire optical wave fronts, digital holography is of great interest to fields such as metrology, display, data storage, and authentication. Fast spatial light modulators exhibiting large light throughputs and good diffraction efficiencies are necessary to provide adequate optical reconstructions of digital holograms. Used in either binary or PWM mode, DMDs have been reported to provide superior light throughput, diffraction efficiency, contrast, and grayscale range relative to transmissive LCD, with no ill effects observed due to the physical movement of the mirrors (4).

Holographic data storage is obviously quite interesting from a business as well as scientific perspective. For many years the storage industry has viewed holographic data storage as having potential for achieving storage density and data rate beyond the limits of conventional optical and magnetic technology. At least two companies today claim storage media capable of superior value for write once, read many (WORM) storage markets such as archival and video. Aprilis, Inc. is shipping 120mm discs for which 200GB storage capacity and 200MB/s data transfer rate are claimed to be possible when used in a properly designed disc drive system.. InPhase Technologies claim 100GB and 20MB/s in the near term with the potential to reach terabyte densities in the future, and are working to demonstrate rewrite capability. Due to its superior switching speed, contrast ratio, and overall maturity, DMD is projected as an ideal device for disc drives utilizing the holographic media. Holographic disc drive developers, including InPhase Technologies and Optware (Japan), have demonstrated systems using the DMD as the digital laser beam modulator.

MICROSCOPY

Over the history of the light microscope much effort has been expended in the pursuit of higher spatial resolution. Optical microscopes reached the so-called diffraction limit more than 100 years ago and indeed this quest for higher spatial resolution has been a vehicle for the development of the diffraction limited and chromatically corrected optical systems of today. Although this progress in resolution has been made largely with improvements in passive optics, more recent advances in microscopy have resulted in the use of active components such as lasers and spatial light modulators.

An SLM finds application in optical microscopy principally as a spatial modulator of the incident or collected light rays. There are a large number of modes of microscopy, such as bright field, dark field, confocal, and phase contrast. In all of these methods light is delivered and collected in a controlled fashion. Control of the illumination and collection cones are accomplished by combining a lens and a diaphragm or aperture (iris, pin hole, annulus, etc.) In a conventional optical system, the diaphragm or aperture is static. An SLM can be used for shaping or scanning either the illumination (Figure 11) or collection aperture of an optical microscope thus to provide a dynamic optical system that can switch between bright field, dark field as well as confocal microscopy. There has been extensive work by Krause, et al (5), MacAulay, et al (6,7) and Hanley, et al (8) using a DMD spatial light modulator as a synthetic, dynamic aperture for microscopy. The reader is directed to these references for more information.

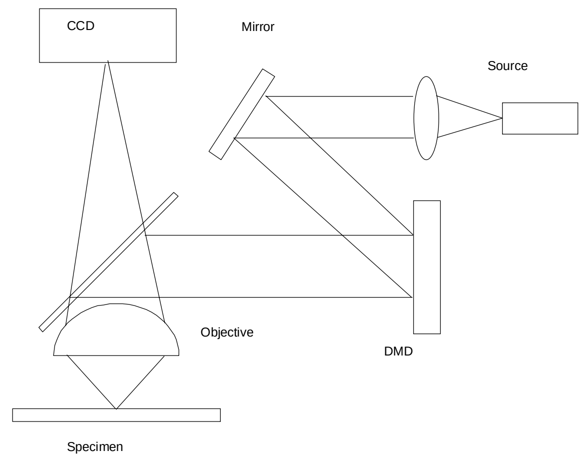

Figure 11. Schematic representation of an optical microscope using the DMD as a scanning aperture

SPECTROSCOPY

The use of DMD SLMs in spectrometry dates back nearly ten years with the first published work that of Wagner, et al (9). A schematic of a DMD based spectrometer is shown in Figure 12. The source light is first collimated and then reflected from or transmitted through a dispersive element. Shown here is a concave grating being used to disperse the light being analyzed. The DMD is deployed as an adaptive reflective slit selectively routing the wavelength of interest to a detector. The DMD can be used not only to select and switch the light of a desired wavelength to the detector, but can also be used to chop the light reaching the detector.

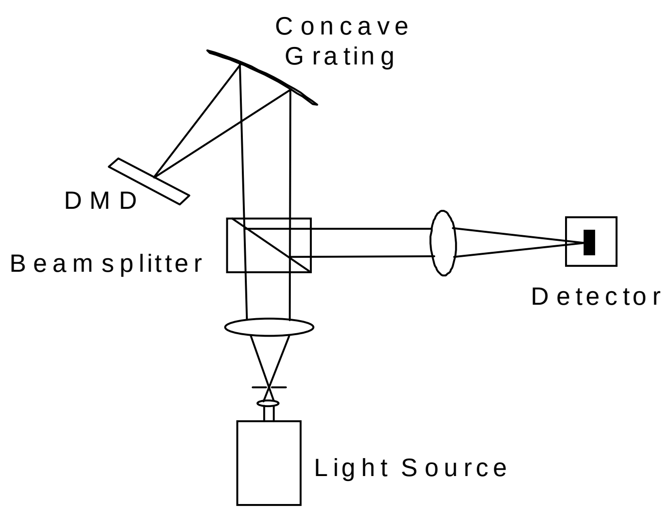

Figure 12. Schematic representation of a DMD-based digital spectrometer.

In the early work of Wagner, et al (9), very early DMD designs were used. In these designs the so-called mirror super structure was exposed and the contrast ratio of the DMD was only about 60:1. The DMDs produced today exhibit contrast ratios as high as 2000:1 and have substantially higher fill factor that the devices used in the earlier demonstrations. Both of these factors will provide higher performing spectrometers than were demonstrable in the early work. More recent work has been presented, including that of DeVerse, et al (10), in which complex transforms are performed using the DMD to significantly improve the signal-to-noise ratio of imaging spectrometers.

SCIENTIFIC AND MEDICAL APPLICATIONS

The projected advances brought about by DMD use in microscopy, spectroscopy, and metrology will enable real time advanced imaging systems for medical and scientific markets. Advanced in-vivo imaging, and perhaps even treatment of cancerous tissue will be possible using DMD-based innovations in combination with endoscopy and other minimally invasive techniques. In-line quality inspection is another projected market, with the DMD used in machine vision systems to evaluate physical parameters and/or chemical composition. The DMD is seeing considerable interest from remote sensing and other security, space, and defense-related markets.

DMD PERFORMANCE HISTORY AND ROADMAP

Through the years the DMD has achieved increasing levels of performance for a wide variety of formats as shown in Figure 13. Several years ago mirror pitch was reduced from 17um to 13.7um, allowing smaller device footprints and associated cost, and data load rate was increased from single data rate (SDR) to double data rate (DDR) for improved PWM capability. The most recent advances have been to 1) increase mirror tilt from +/- 10 degrees to +/-12 degrees, enabling increased optical efficiency, 2) increase projector contrast ratio to >1000:1 by using dark (non-reflecting) metal layers below each mirror, and 3) transition DMD fabrication processes for compatibility with 200mm silicon wafer fabs for increased capacity and reduced cost. Note that projector contrast ratio is very dependent on the optical system. Contrast ratios described in Figure 14 assume f/2.4 optics.

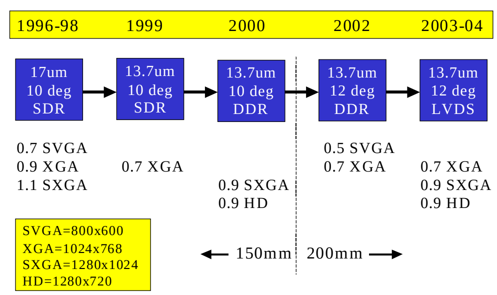

Figure 13. DMD technology advances and device formats.

Next generation DMDs will have additional increases in data throughput as well as mirror transition speed. The 0.7 XGA data rate will be significantly increased from the current 7.6 gigabits/sec data by utilizing an LVDS data interface, enabling frame rate and/or PWM improvements. Because of the strategic importance of entertainment and consumer markets such as HDTV, continued contrast improvement (Figure 14) and cost reduction are major R&D drivers, with long-term emphasis on chip area reduction and low cost package technology. These projector developments should improve DMD properties for non-projector

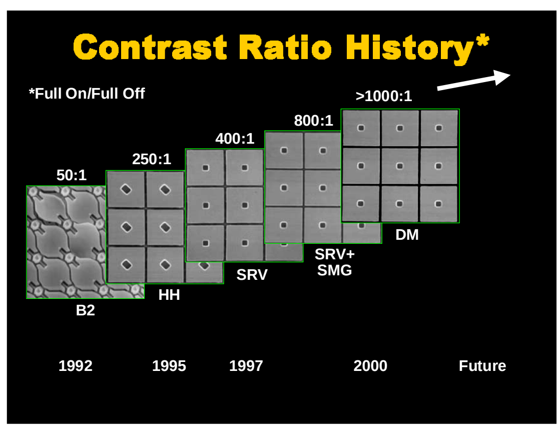

Figure 14. Continuous improvement in full-on/full-off contrast ratio.

applications. For example, next generation package technology may allow improved window transmission properties for UV and other opportunities. However, non-projector applications will not in themselves drive major advances in DMD technology until new hi-volume market opportunities are evident.

PERFORMANCE COMPARISON WITH LCD

As a binary SLM the DMD has significant performance advantages over its closest competitors, and for many potential applications has no current rival. LCD panels used in display applications have orders of magnitude slower pixel response than DMD and are operated in analog mode. Ferroelectric LCD (FLCD) technology is much less mature and difficult to fabricate, but provides binary switching below 100us. While this is still several times slower than DMD, it enables companies such as Displaytech to market a QVGA (320x240) resolution sequential color display using binary PWM. Displaytech claims 100:1 contrast ratio, an order of magnitude below that of DLP™ projectors. Finally, LCD technology is very wavelength dependent and is not considered robust under UV illumination.

DEVELOPMENT PRODUCTS FOR EMERGING APPLICATIONS

In order to enable the myriad of new DMD applications, several issues must be addressed: product flexibility, availability, and support. The same PWM hardware and software that have made DLP™ images so successful in the projector market are too inflexible to address most non-projector or specialty projector applications. The standard DLP™ digital video formatter has therefore been replaced with a flexible DMD controller for the DMD Discovery™ product line. The flexible controller gives the developer full control over data load and mirror reset timing and the ability to operate the 0.7 XGA DDR DMD to its full 7.6 gb/s data rate.

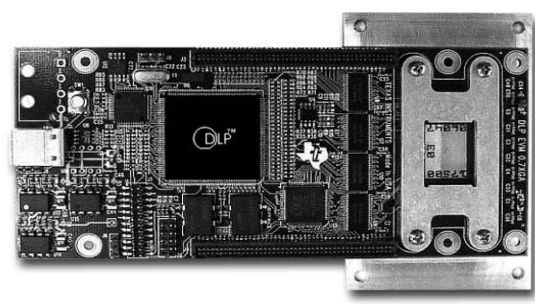

Figure 15: DMD Discovery™ Controller Board with DMD.

The Starter Kit includes the DMD Discovery™ Controller Board pictured in Figure 15, USB user interface software, and a comprehensive documentation package. The Controller Board features a USB port that, when upgraded to USB 2.0 in 2003, will support several hundred DMD binary frames/sec of PC data. In order to utilize the full 9,700 frames/sec DMD capability, there is a hi-speed port with 64 60MHz DDR data lines and 16 control lines. Accessory products that plug into the Controller Board hi-speed port are already becoming available from third parties, providing various data source interfaces and memory functions.

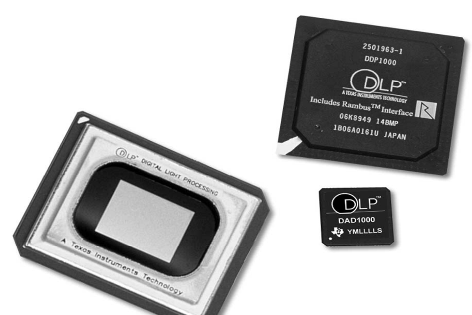

Figure 16. Discovery 1000 chipset with 0.7 XGA DDR DMD, digital controller, and analog mirror reset driver

DMD Discovery™ products are available from value-added resellers that provide product support and may be contracted to develop custom electronics based on the DMD Discovery™ chipset pictured in Figure 16. The chipset may also be purchased from these resellers. Both board and chipset products are marketed to support research projects as well as end-product production of low-to-moderate volume.

SUMMARY

DLP™ technology is now firmly established in a variety of projection display products, enabling brilliant images through digital light switch solutions. At the heart of this technology is the DMD, a dense array of hundreds of thousands of tiny switchable mirrors, whose pixel speed, contrast ratio, and broad spectral capability are unsurpassed by any other spatial light modulator. Many new DMD applications beyond projection display are emerging, and are being enabled through general use DMD products that are now available to developers. These DMD-based innovations will result in a portfolio of exciting new products with the potential to disrupt multiple industries.

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