MEMS Mirror Based Dynamic Solid State Lighting Module

Abhishek Kasturi, Veljko Milanovic, James Yang

Mirrorcle Technologies, Inc., Richmond CA

Abstract

A novel dynamic solid state lighting (SSL) module is demonstrated, allowing users to program the direction, brightness, divergence and shape of a projected white light in a variety of lighting applications. The module is enabled by a fast beam-steering MEMS mirror with high optical power handling. In order to produce and project bright white light, the module illuminates a phosphor target with a high power laser of several Watts. A projection lens projects the phosphor target into a cone of light of up to 60°. This light projection is arbitrarily shaped and dynamically programmable by controlling a MEMS mirror scan head to address specific portions of the phosphor target. An adjustable focus lens in the scan head further allows control of projected beam divergence. Successful prototypes were demonstrated with both a single 445nm laser diode source (2.5W laser power) and with a dual (combined) laser diode sources (5.5W laser power). While the prototypes have to date been limited by available power of the laser sources, it is estimated that the novel MEMS mirror scan head design allows >10W (CW) operation on a 2mm mirror without multilayer dielectric coatings. The introduction of dynamic laser beam steering is a paradigm shift toward a new generation of solid state lighting (SSL) with real-time control of "lighting content".

Author Keywords

MEMS mirror; beam steering; phosphor display; vector display; HUD; solid-state lighting; dynamic lighting.

1. Introduction

State of the art solid state lighting (SSL) technology uses blue LEDs to illuminate near and remote phosphors [1]. More recently, there has been a shift in the industry toward laser-based illumination, where blue laser diodes replace LEDs in essentially the same function, with considerably better control of optical beam properties, wavelengths, etc. This trend toward laser-illuminated phosphor SSL spans from consumer projection displays [2] to automotive headlights [3],[5]-[7]. The technology is constantly evolving toward more efficient laser sources and phosphors and better cooling and packaging solutions for both. Lasers at the 405nm and 445-450nm wavelengths are commonly used in Blu-Ray DVD players, projectors, and have become widely popular in 3D laser printing systems and many other applications where efficient laser sources are needed at a highly competitive consumer price point. Typical efficiency of a single mode 405nm laser diode with approximately 200mW of output power is 20% (~5V and 200mA). As a comparison, green laser diodes, needed to create "white light" achieve at most 5% and remain of relatively low power and very costly. A single laser diode source requires very simple optics without any dichroic mirrors and combiners as used to combine red, green, and blue lasers into a single co-axial beam. RGB lasers are not only difficult to align (especially over automotive temperature range), but they are also relatively costly. With a single laser, complex color control hardware and algorithms are avoided, although color control is challenging with phosphors as well.

Recently, we experimented with displaying a variety of content on emissive films and phosphor plates which emit in various wavelengths for Head Up Display ("HUD") applications [4]. Figure 1a,b images show a comparison of some sample content projected to the transparent film and a phosphor plate, respectively. Content is projected with a 40Hz refresh rate and emission is mostly white. Significant brightness increase was achieved by aluminum-mirror backing of the thin films.

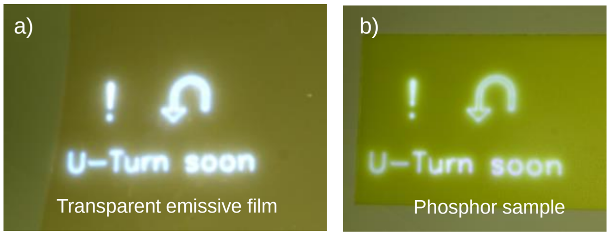

Figure 1. Examples of monochrome vector content displayed on emissive films, excited by a 405nm laser.

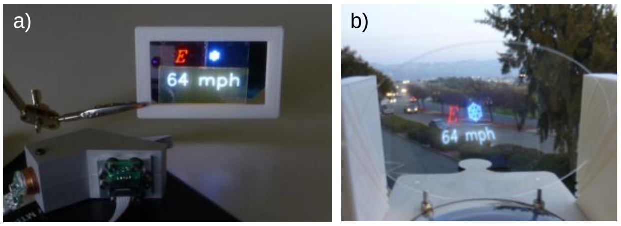

Figure 2. Displaying multi-color content with a 405nm laser and a segmented emissive film screen [4]: (a) a demonstration of concept with a battery powered MEMS mirror scan module illuminating 3 color content on a mirror-backed emissive film plate. (b) demonstration of the film plate in our virtual image HUD prototype.

To create multi-color content we prepared several emissive plates with combinations of films with different emitting wavelength [4]. The concept is based on the fact that HUDs often have content in different colors in separate areas of the display as different colors apply to different types of messages to the driver. In a prototype, we applied a red-emitting film to the top left corner of the plate for warnings to the driver, a blue-emitting film to the top right corner for indicators such as driving directions, and a white-emitting film to the bottom half of the plate for speed and text messages. Each film section was applied to the aluminum mirror, as seen in Figure 2a, and the 405nm scanning laser resulted in a 3-color HUD image which feels more comfortable and informative to the viewer. This plate was inserted into a reflective-version prototype and tested in sunlit outdoors conditions where it gave good readability (Figure 2b). That work [4] clearly demonstrated the ability to create programmable content on emissive phosphor plates which could be projected into distance with adequate projection optics. This leads to the possibility of programmable bright lighting content in more general lighting applications including automotive headlights [5]-[7] which is the focus of present work.

2. Dynamic Solid-State-Lighting Module

Laser Sources and the MEMS Scan Head: A laser module capable of focusing the laser beam to a <25um spot while at the same time not requiring a large MEMS mirror diameter would have favorable optical properties. This is hard to achieve with high power multimode laser diodes available in the 445nm wavelength. Thus we explored two options. One option is to utilize apertures to limit the beam size to better fit on the MEMS mirror, as well as beam reducing optics. Another option is to utilize fiber-coupled laser sources in which case it is easier to optically control the final output beam to fit within the available 2mm mirror diameter and focus to a <25um spot at the phosphor surface. Only modules with up to 2.5W were available for development, in both forms. One of the modules used in experiments and in the transmissive prototype of Figure 3 is a 1.6W laser packaged with a forced-air heat sink, which also includes a TTL laser driver with >2A driving capability.

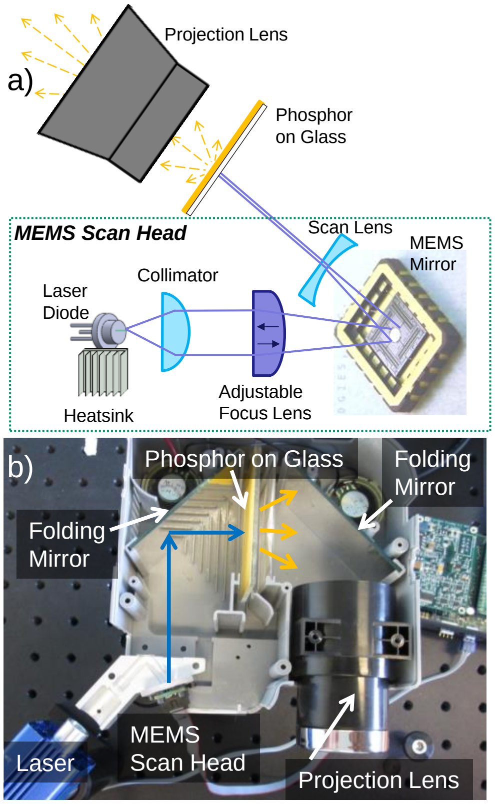

Figure 3: a) Schematic view of the MEMS Mirror Based Dynamic SSL Module with a transmissive phosphor on glass, b) A prototype using a 40° Field of Regard (FOR) Projection Lens.

We explored two optical arrangements for the prototype modules – transmissive (Figure 3) and reflective (Figure 4), as in the HUD work before [4]. In both cases, as seen in the figures, the MEMS Scan Head is identical. Firstly a laser source as described above is collimated. This collimated beam is then beam-reduced by the adjustable focus lens. The nominal state of this lens is to focus the collimated beam at ~60mm distance. This setting results in a minimal spot size on the phosphor. When this focal distance is reduced the resulting spot size on the phosphor grows, producing a larger cone of light in the final projected illumination without any MEMS mirror movement. With relatively small adjustments of one lens element the user therefore has an additional degree of freedom to create programmable illumination of different spotlight size, beam width, or to fill larger areas with illumination as desired. Another method of spot-size adjustment we experimented with was modulation of collimator position with respect to the laser source which has a strong effect while requiring minimal movement. In this method the adjustable focus lens was replaced by a plano-convex 48mm element. After this focusing element, the reducing-diameter beam is delivered to the MEMS mirror at a small incidence angle of 20° to maximize the useable mirror area and scan angle. Finally the beam is scanned by the MEMS mirror through a Scan Lens (-12mm EFL) which focuses it on the phosphor surface while also providing nearly double the scan angle (±20°) than inherently available by the mirror (±10°).

"Transmissive" Laser Phosphor Arrangement: The significant advantage of the transmissive arrangement is the simplicity (Figure 3) – the laser beam delivered from the MEMS Scan Head illuminates the phosphor-coated glass plate from one side while the projection lens gathers and projects the illumination from the opposite side. The downsides of the arrangement however are also very significant. Firstly, the phosphor cannot be adequately cooled by the suspended glass substrate. In our experiments with ~1.6W laser beams we could work successfully in transmissive mode only when the MEMS mirror continuously described some content, at least drawing a circle or a line to spread the power (and heat) over the plate. With a single-pointed laser beam phosphor would be immediately damaged with the blue beam projecting through to the target wall. Secondly, one entire hemisphere of irradiation is not useable in the transmissive setup – a significant loss. For tests, we constructed a prototype as seen in Figure 3b based on a Mini HD projector. We removed its LED light source and its LCD screen, and instead inserted a ChromaLit remote phosphor panel by Intematix and a MEMS Scan Head as described above. Prototype was controlled from a Smartphone and successfully demonstrated the concept (see Figure 7b and Results sec. below).

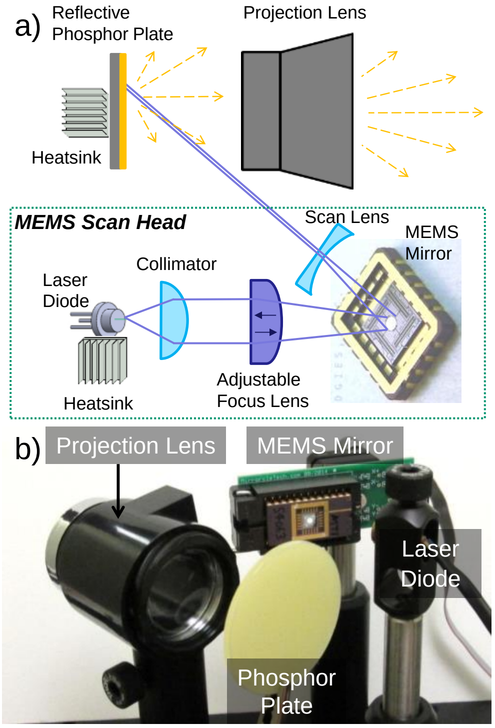

Figure 4: a) Schematic view of the MEMS Mirror Based Dynamic SSL Module with a reflective phosphor plate, b) A simplified optical bench prototype of the reflective laser phosphor arrangement with a socket-mounted 2mm MEMS mirror and a single 445nm laser diode capable of up to 1.2W of optical power.

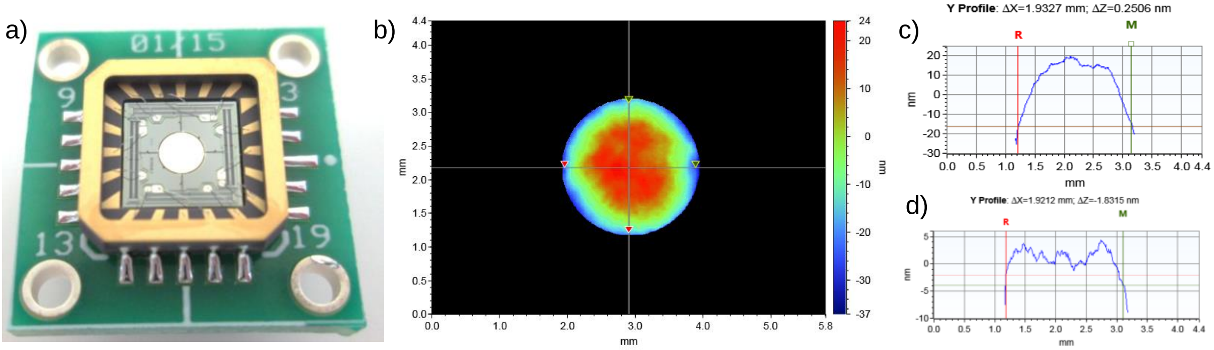

Figure 5. MEMS Mirror Device used in this work (2mm diameter, aluminum coated mirror): (a) Photograph of the device in a 9mm x 9mm ceramic carrier, (b) a 3d microscope scan of the mirror showing maximum tip-to-valley variation of ~60nm. (c) mirror surface profile (radius of curvature -14m), (d) surface profile with the spherical term removed showing <10nm variations.

"Reflective" Laser Phosphor Arrangement: In the reflective version depicted in Figure 4, we excite the film from the same side that is projected. In this case the phosphor film can be deposited directly on a high quality first surface (aluminum or silver) mirror or laminated onto a solid mirror (Figure 2a). The emission from the film is therefore largely directed to one side (the favored hemisphere), with the potential to nearly double the projected illumination. A secondary benefit of the metal backing of the phosphor film is that it allows a proper heat sinking design and construction allowing the use of significantly higher power lasers for additional brightness, as well as eliminating the 'moving laser beam' requirement. Thus the additional illumination and a significant cooling improvement are two major advantages of this method. The dis-advantage is that the laser beam impinges onto the phosphor plate from the side at some angle, requiring some scan-field correction. Namely, it is important that the phosphor plate remains parallel to the projection lens in order to optimize sharpness of projected lighting in all parts of the field of view. But this means that the MEMS Scan Head must address the plate from one side at non-normal angles. Here the ability to arbitrarily control laser beam position and velocity using a gimbal-less quasi-static MEMS mirror is critical – it is simple to correct any projection angle and distortion by altering the control signals to the mirror. A simple test setup with the minimum number of elements to demonstrate the concept is seen in Figure 4b.

3. MEMS Mirror

MEMS Mirror Performance: To achieve a laser-scanning module with flexibility and sufficient size for the laser beam, we targeted a MEMS device design with point-to-point or quasi-static two-axis beam steering capability with significant tip/tilt angle and with a >1kHz frequency response bandwidth. We utilized gimbal-less two-axis MEMS beam-steering mirrors based on monolithic, vertical combdrive actuators [9][10]. The gimbal-less design results in fastest two-axis beam steering with large optical deflections of >20° over the entire device bandwidth, from DC to >1.6 kHz for the chosen 2.0mm diameter mirror. The capability for equally fast beam steering in both axes is a great match for use in laser tracking, laser marking and 3D printing applications, as well as for displaying of vector graphics as in the present work. As mentioned, we had previously demonstrated a highly adaptive MEMS-based display [4] and its application for HUDs. In the HUD application, a device with higher bandwidth was needed to display text content. In the case of dynamic lighting applications, the MEMS device needs to handle higher powers from the laser, and needs to be able to draw simple vector content such as basic shapes, area fills, and other relatively low bandwidth content.

The MEMS mirror device (Figure 5a) is made entirely of monolithic single-crystal silicon, resulting in excellent repeatability and reliability. Flat, smooth mirror surfaces are coated with a thin film of aluminum with acceptable reflectance (approx. 90% for s-polarization) in the wavelengths suitable for phosphor activation, i.e. 405nm-450nm. Flatness of the final, metalized and packaged mirrors is tested on a Bruker 3D optical microscope. Mirrors typically measure over 10m radius of curvature magnitude (|RoC|), like the sample shown in Figure 5b,c,d where maximum peak-to-valley variation is <60nm over the entire diameter. After removing of the spherical term which is easily corrected in optics, the variations drop to <8.3nm (Figure 5d), or approximately $<\lambda/50$ for the 405-450nm wavelengths. With such high optical quality, the mirrors are highly suitable for the 405nm-445nm laser beam steering applications. Another important benefit of electrostatic driving and pure single-crystal silicon construction is an exceptionally wide range of operation temperature. We have demonstrated operation at 200°C and in other researchers' projects mirrors were used at cryogenic temperatures down to ~4°K without alteration. The official specification operating temperature range is a more modest -40°C to 105°C.

MEMS Mirror Driving Methodology: For the prototype setup, a USB-powered MEMS Controller was used which contains a fast MCU, USB and Bluetooth interfaces, and an embedded "PicoAmp" MEMS driver. The PicoAmp is a quad-channel 16-bit high voltage driver which contains an SPI digital input DAC, programmable Bessel filters, a high voltage op-amp, and a voltage booster. The USB-SL MEMS Controller can interface with a host computer through APIs on Windows, Linux, and Android platforms. SDKs in C++, LabView, Matlab, and Java are used to develop examples of generating mirror position waveforms and streaming to the driver. The USB Controller coupled with the development software has real time content generation and display capability.

MEMS Mirror Optical Power Handling: Since the mirror is quasi-static (point-to-point) capable and does not require vacuum for its operation like resonant-type MEMS mirrors [8], it benefits from considerable thermal conduction capability of the surrounding air in its package. This cooling-by-air capability is approximately proportional to mirror area, and therefore increases quadratically with mirror diameter. Especially for larger-diameter mirrors of >=2mm, our experiments and finite-element analyses have shown that the majority of thermal conduction from the mirror's surface is via conduction through the surrounding air. That conduction is to the ceramic carrier below, to the surrounding anchored silicon structures, and to the glass window above. Hence the conduction is inverse proportional to the mirror's distance from those "cool" objects. Although ~10% of the 445nm laser beam is absorbed by the mirror in our experiments, mirrors were found to operate successfully and without any damage to the metallization at up to 4W (CW). This result was obtained with many units in standard packages. In multiple instances mirrors were catastrophically damaged near 4.5W. Silver-coated mirrors showed higher reflectance to increase that range, but require a complex and costly deposition process. Thus we explored two simpler routes to significantly increase this optical power tolerance without need for MEMS mirror re-design or metal coating alteration. One route was to design a new package in which distances between the mirror and cool reference surfaces are minimized (Figure 6). Above the mirror the fused silica window could be dropped from the standard height of 0.65mm above the mirror down to 0.15mm. Below the mirror we placed a custom-designed copper cooling structure which minimizes distances to the mirror without mechanical interference at all possible mirror angles (5.5° on either axis and up to 7.75° on diagonals). This resulted in distance reduction from 0.45mm down to ~0.1mm. With these two simple package modifications which nearly quadruple thermal conductance for the mirror we successfully operated multiple devices at the maximum available power of 5.5W (3 laser beams pointed at the mirror as seen in Figure 6b). We estimate >10W capability with these package improvements. Second route is to hermetically package the mirror in Helium environment - ongoing tests with He packaging will be reported at the Conference. The combination of both approaches should result in 15W capability in full range of ambient temperatures.

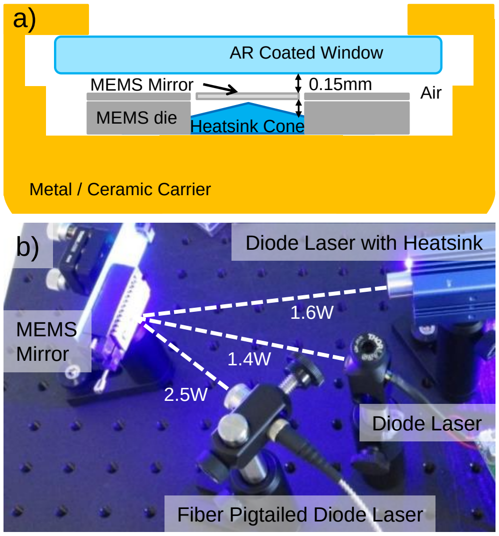

Figure 6: a) A MEMS package optimized for heat dissipation with a lowered window, and a heatsink cone beneath the mirror, b) MEMS mirror power handling test using three laser sources to achieve >5W of CW power.

4. Results

Several mirrors with 2mm diameter were assembled in new thermally-improved air-filled packages and tested with laser beams from single and multiple laser sources (Figure 7a) to obtain the upper limit on power handling capability. No device was damaged with maximum power available in our lab of 5.5W. Further tests will involve higher power sources.

The transmissive projector prototype (Figure 3b) displayed real-time generated content (Figure 7) as bright white light to a test screen several meters away. Movement of content on the mobile device dynamically scans the spotlight over the Field of Regard (FOR) as intended. The FOR can be adjusted depending on the lens used. The projector prototype was limited to 40°. Using an illuminance measurement tool at 1.5m from the projector, up to 140 lux was measured, with a 1W laser source. The reflective optical bench-top prototype using a DLP projector lens (Figure 7a) yielded larger FOR of 60°.

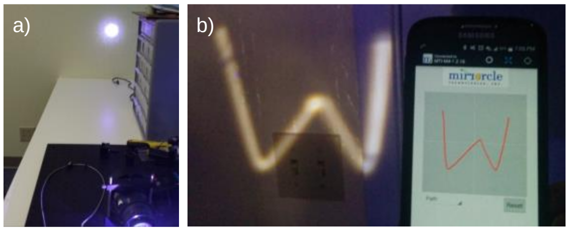

Figure 7: Wirelessly controlled mirror draws content on a remote phosphor plate to display, a) a circular spotlight that is directed by a user to highlight various targets, and b) vector content drawn on mobile device and wall.

5. References

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