Compact and innovative laser beam steering optical engine for smart glasses applications.

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ABSTRACT

Smart Glasses, a subcategory of Head Mounted Display devices, are getting popular in the recent years, offering a convenient way to add information in addition to what the wearer see. Designers are seeking ways to build a Display Engine that can meet the targeted image performance (such as resolution, filed of view) yet keeping the total device size and weight as low as possible. This paper presents an innovative Display Engine based on Laser Beam Scanning (LBS) and outlines the main building blocks that were design and prototyped. It presents the use of MEMS Micro Mirrors (Resonant mirror and Linear mirror) and a newly developed RGB laser light source that integrates the three laser diodes into a single package. This paper outlines the opto-mechanical design considerations, beam and spot size analysis, the driving electronics, mirror and color control loops, the procedures and steps to assemble and calibrate the optical engine and finally presents the achieved results of this work.

Keywords: MEMS micro mirrors, RGB package 3 in1 light source.

1. SHORT HISTORY

Mobile Projection at ST dates back to 2008 when an Israeli startup called bTendo, that was later on acquired by ST, developed the one of the first laser based pico-projector, using ST’s MEMS scanning mirrors.

Since then, MEMS and laser diodes technologies have evolved, and more efficient mirrors and lasers came to market. The increase of laser diodes emitted optical power enabled to project a higher degree of luminosity while decreasing the overall dimensions of the optical module. This enabled ST the great opportunity to open up new markets such as augmented reality and smart glasses, requiring a power efficient and compact display engine. During the recent years, another important breakthrough took place with the availability of new piezo actuated micro mirrors and a compact 3 in 1 RGB laser package, further decreasing the overall engine size and weight.

![Figure 1: Laser Based Optical Engine Evolvement](image)

2. INTRODUCTION
The optical engine (OE) is a laser-based MEMS raster scanning projector. The module is built from two main subassemblies integrated together. The upper base includes the RGB laser light source with collimating optics and the linear (quasi-static) slow scanning mirror. The lower base includes the resonance fast scanning mirror. The module is controlled by dedicated electronics that essentially modulates the lasers and drives and controls the mirrors.

The Electronics subsystem includes:
- Digital Controller - Responsible for video processing, geometric distortion compensation, mirrors control loop, Laser Diode Driver modulation, temperature and pressure compensation.
- Laser Diode Driver – Driving the lasers with appropriate electrical current to generate the right color balance per projected spot.
- MEMS Driver – Drives the MEMS mirrors with right voltage in order to keep the mirror swinging at the appropriate frequency and opening angle.

The Optical Engine subsystem includes:
- Lasers – That emit light in the visible RGB spectrum.
- Optics and relay optics – For beam shaping, collimation and combing.
- Power Detector – Used to calibrate the lasers’ power during operation.
- MEMS Mirrors – Scan the light to project a two-dimensional image.

The above subsystems are synchronized and controlled by dedicated processor and firmware.

Figure 2: Compact and innovative laser beam scanning optical engine and driving electronics.

As mentioned, one of the main goals is to significantly reduce the form factor of the optical engine. In the following chapters we will go over the key design elements that enabled us to achieve this goal.

3. OPTICAL ENGINE CHARACTERISATION

RGB laser diodes 3 in 1 package

Each emitter of the RGB laser package emits a divergent light that is reflected by an integrated reflective folding prism and exits the package thru a sealed exit window. The use of this innovative light source package allowed us to significantly reduce the form factor of optical engine without compromising on the laser power. The use of a packaged RGB laser module compared to the previously use of three separate laser diodes packaged in a standard TO CAN significantly reduced the overall volume, as seen in the below image.
What is MEMS μMirror Scanner

A MEMS micro mirror or scanner is a tiny reflective mechanical device that swings at a given frequency and opening angle. By using collimated laser light source (visible and invisible), light can be steered and spatially modulated (MEMS Scanner). Various applications can benefit from using MEMS scanners thanks to the miniaturization and power efficient technology. There are several actuation technologies that can be used for generating the required force to move the mirror. Such actuators include Electro Magnetic, Piezo based and electrostatic actuators. Specifically, in this paper we have considered the use of an electrostatically actuated mirror that consists of two main parts: The torsional spring and a comb drive. Careful design keeps stress levels in a safe range for long term operation.

Beam scanning

The laser beam is scanned using two uniaxial mirrors, each swinging in one dimension. The Horizontal mirror (aka fast scanner) swings from left to right (and back) in a sinusoidal motion, and by the Vertical mirror (aka slow scanner) swings from top to bottom (and back, known as retrace or blanking) in a linear motion. The combination of the two movements generates a nonlinear “raster scan” that ends in a trapezoidal distorted image. In order to have a rectangular projection only part of the scanned area is used for the projection (active area). A geometrical engine compensates for any geometrical distortion. Additionally, during the retrace the lasers are turned off. Retrace is typically 10% of the total duty cycle.

Raster scanning geometry

Figure 3: comparison between: a) TO38, b) RGB 3 in 1 package

Figure 4: Mechanical structure of a torsional spring and a staggered comb drive fingers.
The system is configured to have an odd number of scan lines: Every frame the beam’s starting position changes. It is scanned from top left corner for the Odd Frames and top right corner for the Even Frames. Interlacing the even and odd scanned frames ensures a full “coverage” of the projection area. The figure below depicts the scanning methodology and the geometrical distortion.

The Image is rastered pixel by pixel, or more accurately spot by spot. The color of each pixel is constructed by the combined RGB lasers. The position to project the combined laser beam spot is controlled by the resonant (Horizontal) and linear (Vertical) mirrors (2 x uni-axial). The Horizontal mirror (Fast axis) scans at a high frequency (21Khz) all columns of the image line, while the Vertical mirror (Slow axis, frame rate 60Hz) scans the complete line onto the projection surface. The resolution (partially) is determined by the Horizontal mirror frequency, opening angle and diameter, while the refresh rate is determined by the Vertical mirror drive frequency.

Optical engine controller functionalities

The Color & Brightness control mechanism sets the brightness, brightness uniformity that ought to be adjusted due to the varying velocity of the fast scanner and the Gamma Correction. Additionally, this mechanism includes temperature compensation algorithms that adjusts the emitted optical power in order to compensate for the possible drift of the laser power and keep the white point stable.

Closed loop operation:

Both the fast and slow scanner require a closed loop driving mechanism in order to keep the: frequency and opening steady despite environmental conditions effects.
The resonant mirror uses a phase lock algorithm to assure high stability in maximum tilting angle and sinusoidal motion. The vertical mirror, which is actuated with a saw-tooth drive, requires a self-resonance cancellation algorithm to avoid artifacts during the projection.

Optical ray tracing

The below ray tracing diagram represents the optical path of our system. The laser divergent light that is produced by RGB package is collimated by dedicated lenses and goes thru beam combiners toward folding mirror, then reflected to resonance mirror. At this stage there it is important to keep the spot size as such that it does not exceed the clear aperture dimensions of the resonant mirror (clear aperture is around 1mm diameter) so we do not introduce any parasitic stary light that could be reflected from the static mirror surfaces, such as the spring or cavity. When the system is working, the resonant mirror is moving and producing horizontal scanned line that is reflected toward the vertical mirror. The linear mirror has much bigger clear aperture compared to the horizontal one, so the scanned line is positioned correctly and symmetrically on the linear mirror when the lens alignment is done accurately. The reflected line from the linear mirror propagates exits the optical engine thru the exit window and onto the desired target such as the glass of a smart glasses device. When both mirrors are in motion, a 2D image with targeted field of view is projected. The figure below illustrates the optical path and laser beam ray trace.

![Figure 8: Optical ray tracing](image)

Optical design considerations

The use of MEMS micro mirror requires an accurate optical design in order to work properly. MEMS micro mirrors are commonly used in diffraction-limited systems, therefore the optical requirements are dependent on the electro-mechanical ones: for example, the projected resolution depends on the mirror diameter, maximum optical scanning angle, laser emitter divergence and wavelength of the light. Figure 9 shows the footprint of the laser spot on the scanning mirror. In order to have an efficient optical path it is highly important to ensure that the laser spot will fit within the mirrors’, as well as any other, optical components’ clear aperture.

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N = \frac{\theta_{\text{max}}}{\delta \theta} \propto \frac{\theta_{\text{max}} D}{\lambda}
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- \(\theta_{\text{max}}\) → max optical scanning angle
- \(\delta \theta\) → laser divergence
- \(\lambda\) → projected wavelength
- \(D\) → mirror diameter

\(\propto\) → proportional
Figure 9: Simulated laser spot footprint on the mirror surface

The Optical Engine key components

Besides the MEMs mirrors (Horizontal & Vertical) that are assembled in a predefined angle one to the other, the optical engine contains the laser light source as well as additional optical and electrical components.

The light source is based on OSRAM’s RGB laser package that consists of several laser diode emitters: Red - 637nm, Green 520nm and Blue 445nm for RGB applications and a collimation lens per each emitter. The main purpose of this lens in our system is to collect the divergent light from LD emitter and to collimate it to a specific focal plane distance (application dependent).

In our system we used Plano-Convex lens with an NA of 0.38, EFL=2mm and 1mm diameter of clear aperture allowing us to collect the laser beam from the RGB emitters with given divergence angles. An anti-reflective (AR) coating is designed for 400-700nm visible spectrum and is applied to avoid stray light and increase the optical path efficiency. The rectangular shape of the lens housing allow us easier manipulation during the optical alignment. Alternatively, we can use a custom aspherical lens for even better optical performance.

Two possible configurations are considered for Beam Combining. The first consists of beam combining and splitting prism and the second consists of three separate dichroic beam plates. Additionally, Polarization optics are needed in order to change or rotate the linearly polarized laser diode light. Possible optical components that can be used for this purpose are half wave or/and quarter wave plates. An Exit window is mounted as a protective element to seal the module against particles. A Photo diode power detector and half ball lens is used to collect some of the lasers light, so proper lasers power calibration and monitoring can be used by the color control loop to ensure the stability of the white point.

4. Assembly, Alignment process & Calibration

Assembly process:

The optical engine requires active alignment of three individual lenses by positioning the lenses and hardening the glue with UV light. The MEMs mirror block consists of two MEMs mirrors that require wire bonding (gold wire). Acceptable technologies for the design and manufacturing of the housing can include, but are not limited to, MIM (metal injection molding), Polymer Injection Molding, Sheet metal stamping or pressing. The selected technology must comply with the required volume, tolerances and manufacturing constraints per the targeted cost and performance.

During the alignment process, the spot size and the spot shape are measured by using adequate measurement tools. Special consideration are given to the spot geometry and diffractions. Once the basic alignment is done the horizontal mirror is opened to obtain an horizontal scan line and then we fine tune the lens alignment by balancing the right/left edges of the scanned line. Also, we consider vertical balancing of the scanned line by moving the lens in Y direction. E pattern test patterns are used to monitor the sharpness of the projected image and further fine tuning is conducted to ensure proper focusing.

Fine tuning adjustment

The spot is adjusted in the center of the image field of view. This adjustment can lead to defocused image at the edges. By looking at the projected line as generated by the horizontal mirror, defocusing/widening of line is observed on the edges. The fine-tuning adjustment goal is to produce the thinnest and uniform line as possible by measuring and optimizing center vs. left and right edges of the projected line. Spot adjustment and optimization of the collimation lenses is considered on three axes.

Once we are done with above optimization, the lens is glued with UV adhesive.
Color offset alignment process:

The color offset between all three laser spots is kept to the minimal in order to support the best image quality and which typically are within 0.2-0.5deg. Once all three lenses are aligned and glued, we perform measurements with a beam analyzing camera to capture and measure the spot parameters and a power meter to measure the optical power. The Optical Engine cover is glued at the end of the alignment process with UV adhesive. The system is passed to system integration and calibration as the next step.

Spot size analysis:

The laser beam can be collimated, by using the collimation lenses, to different focal plane distances (FPD) from near field to infinity. This process is done by manipulating the lenses in five mechanical axes (x, y, z lateral movement and x/y tilts) against the light source. The typical spot size at far field (1.5m) when using long distance collimation as FPD (green laser as an example) is about 2.1x1.6mm. The typical spot size at near field (30mm) when using short distance collimation as FPD (green laser as an example) is about 0.15x0.1mm. When the alignment is performed optimally, the center of gravity of the Gaussian beam is well centered which allows us to keep the best optical and imaging performance of the overall system. The system is passed to system integration and calibration as the next step after all measurements are done.
Figure 12: a) center of gravity, b) laser spot size

System calibration:
Once all optical alignments are done, the Optical Engine goes through two calibrations procedures. The first calibration procedure handles the lasers power, luminosity and white balancing. The second calibration procedure handles the MEMS mirror related parameters and include Geometrical distortion correction of the projected image, the horizontal and vertical field of view and aspect ratio of the image as well as the color brightness and uniformity. The figures below shows the calibration stations.

Figure 13: Laser power calibration setup

Figure 14: Mirrors calibration setup

5. Conclusion and future work

The purpose of this study was to design, prototype and characterize a compact and innovative laser beam scanning optical engine based on ST’s MEMS Micro mirrors for smart glasses applications.
As observed, an ultra-small engine capable of generating color images at high resolution and sharpness was achieved. Future work could explore possible designs and technology to achieve higher resolution optical systems (such as by multiplying the number of RGB sets), the integration of more advanced beam combiners (such as Planar Light Circuit) and the integration of few optical elements for further size and weight reduction.

6. REFERENCES

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