Converting a Texas Instruments DLP4710 DLP evaluation module into a spatial light modulator

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Digital Micro-mirror Devices (DMDs) are a popular alternative to liquid crystal spatial light modulators for laser beam shaping due to their relatively low cost, high speed, as well as polarisation and wavelength independence. Here we describe in detail how to convert a low-cost digital light projector (DLP) evaluation module which uses a Texas Instruments DLP4710 DMD into a spatial light modulator using a 3D printed mount. The resulting device is shown to accurately shape Laguerre-Gauss modes, can operate in real-time over HDMI without modification with a 180 Hz hologram refresh rate, has a resolution of 1920×1080 pixels and a diagonal screen size of 0.47 inches.

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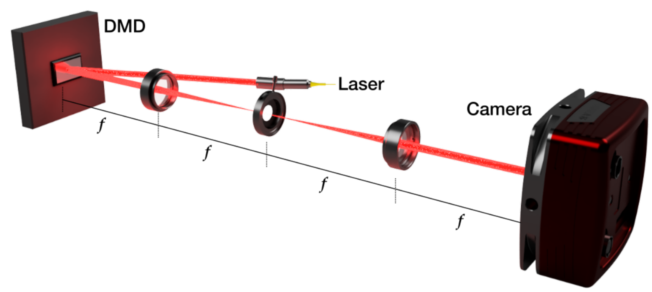

Fig. 1. A typical experimental layout with a single mode fibre-based laser source, a DMD, a spatial filter and a camera. For the demonstration tests presented here we used $f = 100$ mm lenses and a 635 nm single-mode coupled laser diode source collimated to a beam diameter of 2.1 mm.

1. INTRODUCTION

Digital Micro-mirror Devices (DMDs) were developed in the 1980s and 1990s and are now primarily used in digital movie projectors due to their high-contrast and high-power handling capabilities [1]. More recently, they have become a useful experimental tool that are now used in various optics experiments and applications such as structured light, microscopy, photolithography and single pixel imaging to name a few [2–8]. Here we focus on the use of DMDs as polarisation and wavelength invariant computer generated holograms for structured light applications such as mode creation and detection, wavefront sensing and polarimetry [9–14]. The presented arrangement, however, is such that the DMD may find use in many other applications.

A DMD is a 2D array of micro-mirrors spaced several micrometers apart with the ability to be electronically tilted to an "on" or "off" position, usually to direct incident light toward or away from a target [12]. The resolution of modern DMDs is on the order of hundreds or even thousands of pixels in each dimension. Typically, the available resolutions follow common display standards and so 1920×1080 (Full HD) is readily available, but higher and lower resolutions are available (at higher or lower cost).

In order to use a DMD as a so-called spatial light modulator, the bare DMD must be situated such that an incident laser beam and required experimental components can be conveniently located. Some DMD development modules are sold without optics such as the Texas Instruments DLP 6500 EValuation Modules (EVM) [15] and DLP Discovery 4100 Development Platform [16], and are usable with a custom mount and no further modification. Here we focus instead on the Texas Instruments DLPDLCR4710EVM-G2 which is significantly cheaper (and thus more accessible to researchers with a tighter budget) than other DMD evaluation modules currently available, while also having specifications highly conducive to structured light experiments [17]. A physically similar module, the DLP4710EVM-LC is also expected to work using the modifications described here [18]. Unfortunately, both DLP4710 EVM models have pre-installed projection optics which must be removed before they can be used.

In Sec. 2, a typical experimental setup for mode creation is provided, as well as a brief summary of how holograms for DMDs can be created with references to some tutorial papers for the interested reader. This setup and generation method is used to test the performance of the modified DLP4710 EVM with some test results also presented. Section 3 details the required modifications, 3D printed components and firmware configuration to use the DLP4710 EVM as a spatial light modulator.

2. SHAPING LIGHT WITH A DMD

Since the DMD can be re-purposed as a digital hologram, it can be used to structure light, with a comprehensive tutorial in

Ref. [12]. It is out of the scope of this paper to go into detail on the various possible techniques to do this, but for the purposes of demonstrating a working device, some brief background is given in this section.

A minimal experimental setup is shown in Fig. 1, where a collimated Gaussian laser beam is reflected off the DMD, where the first-order is then spatially filtered using a $4f$-system using an adjustable iris aperture and finally imaged using a camera. We use this setup to test and demonstrate the capabilities of the DLP4710 DMD, described in Sec. 4.

A DMD is an amplitude-only device and cannot inherently modulate the phase of light, which is required for complex beam shaping. In order to encode a field with both amplitude and phase components a special grating function is used to create a binary, amplitude-only hologram [12, 19]. The transmission function of this type of hologram is given by

$$T = \frac{1}{2} + \frac{1}{2}\mathrm{sgn}\left\{\cos(2\pi\psi_G + \psi_U) + \cos\left[\arcsin\left(\frac{A}{A_{\max}}\right)\right]\right\}, \quad (1)$$

where ψ_U and $A/A_{\max}$ are the phase and normalised amplitude of the desired complex field, U, respectively (for example Eq. 2, which describes a Laguerre-Gauss (LG) mode) and ψ_G is a linear phase ramp which defines the period of the resulting grating. Examples of what the binary holograms look like with LG modes are shown in Fig. 5 (a).

LG modes are solutions to the scalar Helmholtz equation in cylindrical coordinates [20]. They form an orthonormal basis and are also Eigenmodes of free-space, making them useful for long-distance propagation, for example in multiplexed wireless optical communication [21]. At the plane of the DMD (i.e $z = 0$) they are given by

$$U^{\mathrm{LG}}_{\ell,p}(r,\phi) = C^{\mathrm{LG}}\left(\frac{r\sqrt{2}}{w_0}\right)^{|\ell|} L_p^{|\ell|}\left(\frac{2r^2}{w_0^2}\right)\exp\left(-\frac{r^2}{w_0^2}\right)\exp(-i\ell\phi), \quad (2)$$

where ℓ and p are the azimuthal and radial mode indices respectively, w_0 is the beam waist, C^{LG} is a normalisation constant and $L_p^{|\ell|}(\cdot)$ is the generalised Laguerre polynomial.

LG modes are identifiable as they appear as donut-shaped rings on a camera in a setup such as in Fig. 1. Larger azimuthal indices result in larger diameter rings and radial modes manifest as rings around the bright, central ring. Even small aberrations on the surface of the DMD will result in these rings becoming distorted. This is a convenient qualitative measure of the DMDs beam shaping performance.

If the resulting beam quality is insufficient, a correction phase can be added or subtracted to the hologram. The Gerchberg-Saxton algorithm can be used to find this phase, or alternatively, suitable Zernike phases can be added or subtracted in a "trial-and-error" manner [10]. As a last resort, one can reduce the size of the encoded beams to limit the exposure to the aberrated area.

3. HARDWARE AND FIRMWARE

The DLP4710 DMD from Texas Instruments has an array size of 1920×1080 pixels with a pixel pitch of 5.4 µm. This results in an active array size of 10.4×5.8 mm (or 0.47 inch diagonal). The DMD is available on two affordable evaluation modules, both of which can be modified for laser-based experiments. In this work the DLPDLCR4710EVM-G2 was used, but the DLP4710EVM-LC appears to have the same dimensions as it seems that only a different chipset is used (See. Sec. C) [17, 18].

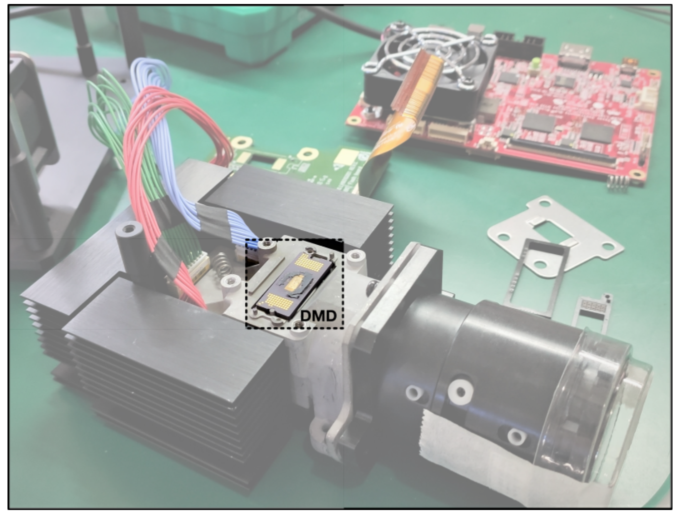

Fig. 2. A photo of the DLP4710 EVM with the main PCB removed, showing the un-soldered DMD positioned in the projection optics module.

The 3D printed assembly is described in Sec. 3A, as well as some firmware configuration changes, described in Sec. 3B. Holograms are displayed on the DMD via the HDMI connection, as the EVM simply shows up as another monitor. We describe how to display holograms at a rate of 180 Hz over HDMI in Sec. 3C.

A. 3D Printed Assembly

There are two reasons why a custom mounting assembly is required for the DLPDLCR4710EVM-G2. The first is that the bare DMD chip must be positioned vertically at a height that is suitable for standard laser-based setups. Unfortunately, the DLP4710 DMD is not soldered to the board in this EVM and so simply stripping away the projection optics is not an option. A precise assembly is thus required to hold all the components in alignment.

As is visible in Fig. 2, the DMD is precisely slotted into the projection optics and uses a spring-loaded inter-poser shim for the electrical signals to a PCB (Printed Circuit Board) which is screwed down with heat-sinks to hold everything in place. A precision assembly is therefore required to hold the DMD in place on the circuit board in the absence of the projection optics. A photo of the custom assembly is shown in Fig. 3 (a) and (d).

Two plastic components must be printed at high resolution. Here an Ultimaker S3 at 0.1 mm layer height with "Strong PLA" filament and 80% infill was used to create a rigid and accurate structure. Figure 3 (b) shows the mount plate, which holds everything in position and allows for a standard M6 cap screw and optical post to be attached. Figure 3 (c) shows the more intricate cover plate, which has "pins" to hold the DMD, shim and PCB in precise alignment. No additional screws or hardware are required as the design is such that the existing screws and springs from the EVM can be used, as shown. The design caters for M3 nuts on the front of the cover plate for added strength and reliability, if required. The design files in both STEP and STL formats are available online [22].

To assemble, carefully slot the DMD face-down into the cover plate, then the shim and then place the PCB. Everything should slot into place. The square-shaped metal plate is placed behind

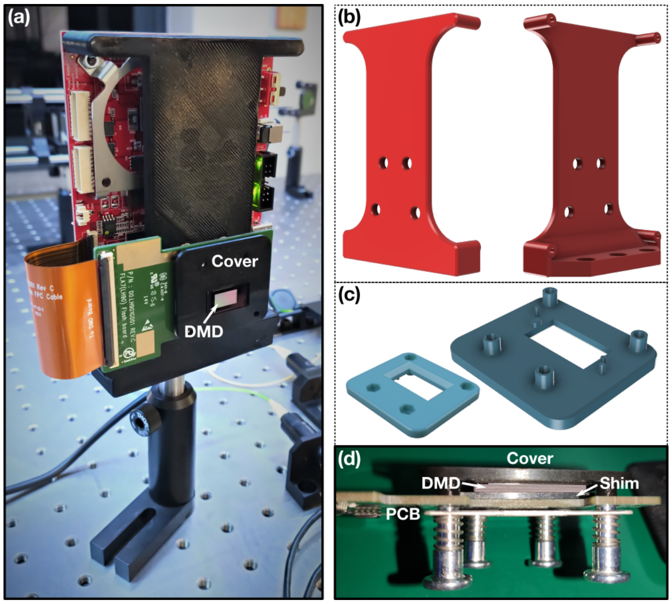

Fig. 3. A photo of the completed unit (a), with renderings of the 3D printed mount (b) and DMD cover (c). The key component is the cover, which has several alignment pins to hold the DMD, inter-poser shim and PCB in exact position (d).

the PCB, as it was before the DMD was removed from the light engine. Figure 3 (d) shows the resulting arrangement. In reality, the assembly requires the screws to be inserted through the mount plate (Figure 3 (b)) first, after which the springs are placed. While holding everything together in position, gently and carefully turn the screws so that they grab the cover plate. Incrementally tighten diagonally opposite screws until the assembly is rigid.

Do not over-tighten these screws as the plastic can be stripped. There is also a possibility that the DMD is warped if things are too tight, but the use of the shim largely prevents this, ensuring optical flatness. It should also be noted that there is a specified maximum clamping load of 110 N (Sec. 6.9 in the DLP4710 datasheet), but we are unable to verify this and assume that this load is not exceeded as the original clamping springs are used.

Remove the fan from the top of the main board. This is not required as the LED driver circuit will not generate any heat with no LEDs connected. There should now be space to mount the cover assembly to the main PCB. Use the remaining screws to assemble everything as shown in Figure 3 (a). During this entire procedure, be careful of electrostatic discharge. A grounded wrist strap is recommended, and working on a grounded metal table or anti-static matt is also a good idea.

B. Firmware Configuration

By default, the firmware expects there to be LEDs connected. The module will not power on correctly if it detects that these LEDs are not present. In addition, the default mode of the device is to display a demo graphic and so this must be changed to the HDMI input. Fortunately, the configuration can be modified and saved into non-volatile memory.

Download and install the configuration utility from the DLP4710EVM product page [17]. Instructions are available from Texas Instruments to do this, and how to troubleshoot any issues that may arise. Using the utility, a so-called "batch file" can be created and flashed to the EVM to update the configuration on startup.

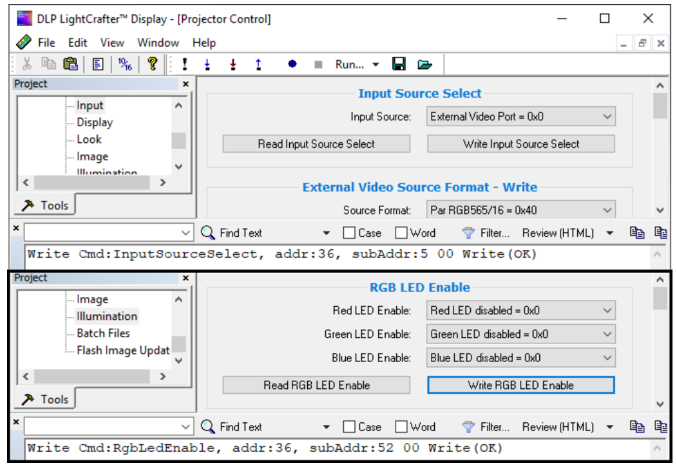

Fig. 4. Screenshots of the configuration utility in Advanced mode showing the HDMI source selection (top) and LED disable configuration (inset bottom).

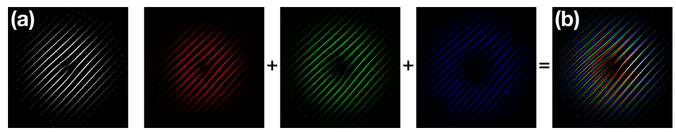

Fig. 5. (a) A typical binary hologram for a DMD of an LG, $\ell = 1$ hologram for up to 60 Hz operation over HDMI. (b) The resulting hologram image with three consecutive LG holograms with $\ell = 1, 2$ and 3 for 180 Hz operation.

The contents of this batch file, which is simply a text file with the extension ".bf", are shown in Lst. 1. The specifics of how to install this file into non-volatile memory is left to the reader as the instructions are available from the manufacturer. For convenience, Fig. 4 shows a series of screenshots of the configuration utility highlighting the LED and input source configuration which can be done after the DMD is turned on, if the batch file method is not desired.

```
# Write: InputSourceSelect
W 36 05 00
# Write: RgbLedEnable
W 36 52 00
```

Listing 1. Batch file contents for the DLPDLCR4710EVM-G2 to disable the LEDs and switch to the HDMI input.

C. High Speed Display over HDMI

The specified frame-rate of the DLP4710 EVMs is 60 Hz over HDMI, and so holograms can be displayed at this rate without any special techniques. As an aside, the DLP4710 DMD itself supports 120 Hz and so the 60 Hz limitation is due to the chipset and firmware. Screen tearing or missed frames might occur at rates close to this frequency unless synchronisation to the screen refresh rate is used. Techniques to do this depend on the software and operating system and will not be detailed here.

With an understanding of how the DMD modulates the Red (R), Green (G) and Blue (B) channels for 24 bit colour, we can in fact display different binary holograms at a rate of 180 Hz or even 1440 Hz [23]. Here we describe how to update the DMD at 180 Hz as no special configuration is required to do so. It should be noted that some DMD EVMs support the loading

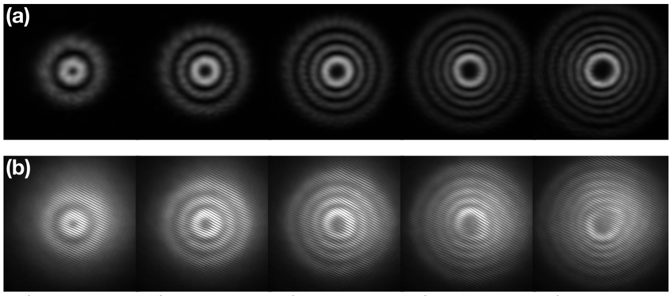

Fig. 6. (a) Example LG beams generated using the device with slight aberrations visible as deviations from a round shape confirmed by (b) which are Mach-Zehnder interferograms of the beams showing some curvature of the fringes and vortex splitting. The intensity variations in (a) are due to a sub-optimal grating period and possibly some interference with the zero-order, which could be removed with a smaller spatial filter.

of images into the DMDs memory and playing them back at several kilohertz. This mode of operation is not supported on the DLPDLCR4710EVM-G2.

The DMD rapidly switches between the red, green and blue channels while synchronously toggling the corresponding coloured LEDs, to create the perception of a colour image. A black and white image is in fact displayed as three separate, sequential frames: the first is black and red, then black and green and finally black and blue. By encoding different holograms (or images) as each of these three colours and then merging them into a single image, the resulting "effective" rate is 180 Hz (if these images are displayed at 60 Hz). Figure 5 (b) diagrammatically shows what the displayed hologram might look like. As an example, Lst. 2 shows the MATLAB code to generate this RGB image from three binary images, since colour images in MATLAB are represented as 3D matrices. Example code for demonstrating this technique, as well as for displaying these colour images full screen as holograms on the EVM, is provided online [22].

```
function [imgCombined] = Combine180(imgA,imgB,imgC)
    imgCombined = cat(3,imgA,imgB,imgC);
end
```

Listing 2. Generating a combined image to achieve 180 Hz hologram rate.

4. TEST RESULTS AND DISCUSSION

In order to perform a rudimentary test of the performance of this DMD, LG modes were generated with $\ell \in [-5, 5]$ and $p \in [0, 5]$, with the code available online [22], using a similar setup to that given in Fig. 1. The incoming beam had a $1/e^2$ diameter of 2.1 mm and the encoded beams had $w_0 = 1$ mm.

The holograms for each mode were generated, displayed on the DMD and then the resulting beam was captured with a camera. These images were inspected and the modes are high quality. Figure 6 (a) shows a selection of images of these modes. Some distortion is visible on the largest mode, indicative of minor aberrations.

This is confirmed by the interferograms shown in Fig. 6 (b), generated by interfering the incoming Gaussian beam with the resulting mode. The fringes on the interferograms should be straight, with a fork at the centre with a number of "tines" depending on ℓ. Some curvature is visible as well as some vortex splitting. While taking these measurements we noted that the mount is quite sensitive to vibrations. This is due to the vertical arrangement and the low rigidity of the plastic. The design was modified to increase the rigidity and in future versions we plan to improve it further.

We speculate that the relatively insignificant aberrations of this particular DMD (compared to the DLP6500 used by one of the authors previously [9]) are due to two reasons. The first is it's relatively small size which limits bending. Second, we believe that the main reason for the high flatness of this DMD is because it is not soldered down. It is possible that the process of soldering the DMD causes differential expansion and contraction as the solder cools, deforming the DMD. In a projection setup these aberrations would be of no consequence, but for beam shaping a fraction of the wavelength has an impact.

High speed operation at 180 Hz was also verified by combining three different LG beams into a single RGB image and observing the laser beam using a camera running at 500 Hz. Unfortunately there is no output trigger signal on the DLPDLCR4710EVM-G2 which could have been used to trigger the camera in sync to the frame changes, and so oversampling was necessary. If this signal is required, it is available on the DLP4710EVM-LC, according to the datasheet.

5. SUMMARY

Spatial light modulators have become a staple component in laser optics labs working with structured light. Digital micromirror devices are versatile, fast and affordable and are an excellent alternative to conventional liquid crystal spatial light modulators. DMDs are not yet available as off-the-shelf as scientific instruments and so evaluation kits usually in the form of digital projectors must be purchased and modified.

We explain in detail how the Texas Instruments DLP4710 evaluation modules can be modified for laser beam shaping with some 3D printed components and firmware configuration. We visually tested the resulting device with a range of LG modes and find the device to be remarkably aberration-free.

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