Spatial structuring of light for undergraduate laboratory

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Abstract

In recent times, Spatial light modulators have become a common tool in optics laboratories as well as industrial environment to shape the spatial structures of a beam. Although these devices are often easy to use, they usually come at a high cost such that they are far from being implemented in undergraduate laboratories. However, over the last years, the progress in developing more cost-effective projectors has led to affordable spatial light modulators in the form of so-called Digital Micromirror Devices (DMD). This reduction in price, as well as their simple usage, make DMDs increasingly suitable for undergraduate laboratories to demonstrate optical effects and the shaping of light fields. Here, we explain in detail one of the most cost-effective ways to make a DMD available and how this low-cost spatial light modulator can be used as a valuable tool for undergraduate laboratories. We characterize the diffraction efficiency of the device for the most commonly used laser wavelengths that are also widely present in the teaching laboratories. Most importantly, we demonstrate beneficial use of the low-cost light modulator in various optics experiments ranging from single and multi-slit diffraction, to optical Fourier transformations and Fresnel zone plates. Finally, we show that it can further be utilized as a re-programmable amplitude hologram to generate different spatial modes, e.g. Laguerre-Gaussian beam, which are one of the most commonly used spatially structured beams.
I. INTRODUCTION

There is a lot of focus on the structuring light to enhance various applications in the modern research fields, varying from microscopy to ultrafast pulse shaping to optical communications, optical trapping and quantum technologies. All of these fields require methods to shape the transverse beam profiles using the so-called spatial light modulator (SLM). The SLMs themselves are devices that impose a transverse spatial modulation on a beam of light using either phase, amplitude, spatially varying polarization modulations, or their combinations. The great benefit of most of these devices is that they can be flexibly controlled by a computer using appropriate programs, such that their modulations can easily be adjusted to the specific field of applications or the task they perform. These modulators are composed of 2D-array of micron-sized pixels so that the modulations can be applied accurately with the precision of 8-10 microns and often in a 2-, 8-, or 16-bit modulation depth. Obviously, such devices would be very beneficial not only in research and applications, but also to demonstrate various optical effects and showcase simple applications using structured light. Hence, SLMs are also a great tool in undergraduate student’s laboratories for demonstrating various optical phenomena. However, many SLMs produced for such purposes are expensive for simple experiments like studying diffraction and basic interference properties of a light beam in undergraduate laboratories.

To be able to make SLMs available to students and interested scientific enthusiasts on a frequent basis, more cost-friendly approaches are in demand. While there are suggestions to utilize commercially available projectors as a way to implement a cost-effective solution to that problem, the described approach strongly relies on actual brand and, thus, on the availability of those devices. In this work we describe how to utilize a cost-effective and readily available SLM based on a digital micromirror device (DMD). As DMDs are commonly used in cost-effective projectors, they are often significantly cheaper than other SLM variants on the market. Moreover, we show how a very cost-effective evaluation module, including a DMD together with a single-board computer, can be turned into a versatile and convenient-to-use spatial light modulator.

Our approach utilizes a combination of BeagleBone Black (BB) and DLP LightCrafter Display 2000 Evaluation Module (EVM), both manufactured by Texas Instruments (TI). The device BB is a single board computer, and the EVM is a projector which contains
DLP2000 DMD, which will be the essential part when used as a spatial light modulator. These devices, combined, provide a low-cost SLM with a Linux-based platform and usually costs less than 200 dollars\textsuperscript{10}. The implications of such a setup are quite profound, allowing a low-cost and easy-to-use SLM to be implemented in undergraduate laboratories. We demonstrate a few examples that could be used as showcases for the students’ experiments ranging from diffraction to interference, to Fourier optics to holography and beam structuring. Especially the latter might also be interesting for more advanced graduate courses and could be also utilized in demonstration experiments in outreach activities.

II. IMPLEMENTING THE DMD IN UNDERGRADUATE LABORATORIES

The evaluation module (EVM) features the DLP2000 chip-set comprised of the DLP2000 0.2 nHD DMD, DLPC2607 display controller and DLPA1000 PMIC/LED driver. The DLP2000 DMD has a resolution of 640×360 pixels with 7.56 µm micromirror pitch.

The current section provides a detailed description of the modulating device, such that it can not only be utilized efficiently, but its underlying functionality can also be understood. The section is divided into three parts: understanding the micro-mirrors of the DMD, preparing the device for optical experiments, and finally it’s proper operations.

A. Understanding DMD configuration

The light modulator, we used, modulates the light by shaping its transverse amplitude, i.e. it enables to mask the light field by adjusting the direction of the reflected light with pixel-to-pixel flexibility. This spatial-amplitude modulation is achieved by adjusting the arrays of micro-mirror DMD. Here, each micron-sized mirrors can be used to keep or remove the light’s amplitude at a specific transverse position by reflecting it in or out of the direction of observation. We note and demonstrate later that such an amplitude modulation also allows for phase modulation through amplitude holography, which will be discussed in section III E.

In order to obtain the required modulations, the micro-mirrors of DLP2000 DMD can be aligned in three different positions a) off-state, b) on-state with black information, and c) on-state with white information (see inset in figure 1a). The tilt angle between the off- and on-state is about 10-12%. Although we use the device as a static spatial light modulator
only slowly varying the displayed binary modulation patterns, it is worth noting that such devices are mass-fabricated for the use in projectors. Here, the pixels are usually switched very fast, such that the three different encoding colors (red, green, blue) are modulated consecutively synchronized to different arrangements of the mirror array to form a proper color image. However, we will not use this fast switching ability, but note that this might be another interesting feature to test in undergraduate laboratories and has been used research tasks. If a transverse coherent light field, such as a laser, impinges on the DMD screen, the pixelization and space between the micro-mirrors (limited fill-factor) cause the light to be not only diffracted into the desired direction but also a 2D grid pattern. Hence, even when the DMD is switched off but illuminated with a laser field, their will be a diffraction pattern visible, which is caused by the pixel pitch of the DMD.

FIG. 1. Experimental setup. a) Sketch of the experimental setup. A laser illuminates the DMD screen, which modulates the transverse beam profile. A camera records the modulated image or its Fourier transformation (FT), shown in the inset on the left, depending on if and where a lens is put into the beam path of the reflected light (see main text for more details). The inset on the right shows the functioning of the DMD screen, which consist of many small mirrors, which can be in three positions depending on if the device is switched off or the color black or white is displayed. b) Photo of the DMD screen (from the DLP DLCR2000 EVM) mounted on a mirror mount and connected to the driver board and BeagleBone black.

Another interesting fact also relying on the working principle of the DMD, is that since the
unwanted light is not absorbed but rather reflected into a different direction (see figure 1a), the inversely modulated light field can also be always observed. While the inverse amplitude can sometimes lead to completely different results, it produces for most holography the same light fields. Finally, depending on the wavelength of the laser, one can also observe a reflection of the beam in between the wanted and unwanted modulated light fields. We attribute this reflection to stem from the screen surface window and its coating from the DMD.

B. Preparing the DMD

The DLP lightcrafter is plugged into the BeagleBone black (BB) to get an embedded DLP projector device. Both, DLP lightcrafter and BB, are connected to 5V power source each. The BB can also be powered using the micro-usb port and might be connected with a network cable for remote operations. After the device boots up, a Debian desktop appears. Here, we recommend starting the system first in its original states as a projector to verify its proper functioning and obtain the IP address. To do so, it is convenient to have a keyboard and a mouse also connected to the BB. Once the projector is running, one can open the terminal from the menubar on bottom-left and enter the command `ifconfig`. The line starting with `inet` contains the IP address of the board. This address will be later required to access the board from a computer remotely.

After having tested the device as a projector, one can now turn it into an SLM. This procedure is simple, however, requires precise and careful handling of the device. The essential step of this transformation is to separate the DMD DLP2000 from the optical engine and expose it for direct optical use. This can be done by removing the screws, which secure the DMD and then separate the DMD by cutting through the glue with which the DMD is attached to the optical engine. Although the optical engine is not required in the experiment, we do not recommend removing it from the board as this can raise issues and even stop the DMD from working due to a fail-safe configuration. We suggest to either keep the LEDs ON during experiment or manually switch them off with a series of commands that needs to be input in the console terminal of the BeagleBoard (see Appendix for more details). If the device is not operated in a light-sensitive environment, having the LEDs working was very useful, as they serve as a good indicator of the device being active. For
light-sensitive applications, one can cover the LEDs with thick black paper or plastic sheet for the proper blockage of light.

The final step to mount the system for use in optical experiments. For this, we glued the DMD screen onto a 3D-printed disk with 1 inch diameter to enable mounting into a commonly used mirror mount. For the control and driver unit, we also 3D-printed a holder, which also allowed its flexible positioning on a breadboard or optical table (see Fig. 1b). With these adjustments, we now obtained a fully function DMD as a simple but very versatile spatial light modulator.

C. Operating the DMD

For the operation of the DMD as a versatile light modulator, it is required to display a variety of modulation patterns, e.g. gratings or holograms of different types. As the device modulates the amplitude in a binary fashion, i.e. ON and OFF, it is the best to use black and white (binary) images only. In general, the device’s processor could be powerful enough, such that one can run a special program to prepare and display the required modulation pattern on the device itself, e.g. through a computationally effective program written in either Python or C/C++. In our case, the binary images were produced using MATLAB on a standard desktop computer and transferred to the device. To transfer and display the modulation patterns onto the DMD, another computer on the network is used to connect to BB using SSH and SFTP protocols. Through this connection, one can transfer files via the program WinSCP (or similar ones). We further established an SSH connection using Putty to send commands and control the display. The BeagleBone Black also has a micro-SD card slot, which can be used to increase the storage capacity of the device.

For Putty and WinSCP connections, the user will first need to enter the IP address of the device and then the username and a password. The default username for a BeagleBoard is Debian and the password is temppwd. After the connection has been established, the BB is ready to receive commands from the user. As the BB does not have an image viewer software, we chose Feh image viewer for its simplicity and lightweight. The command for installing Feh viewer is sudo apt-get install feh. After the viewer is installed, the board is ready to operate with images. The most useful commands to operate the device, i.e. to display the light-modulating patterns, are the following:
• `export DISPLAY:=0`, a command that creates variable `DISPLAY` which in turn tells the device to display the image on the first display on local device, which is DMD.

• `feh -F image-name`, a command that tells the `Feh` viewer to display the desired image. `-F` suffix specifies it to be done in full screen. `Feh` opens any format supported by `imlib2`, most notably `jpeg`, `png`, `pnm`, `tiff` and `bmp`.

• `control+c`, is a combination of key to close the `Feh` image viewer, which leaves the `debian` desktop.

The DMD is now ready to be used as a versatile programmable light modulator for spatially structuring a light field.

### III. EXPERIMENTS FOR UNDERGRADUATE STUDENTS

After having introduced the device and its operation, we characterize its wavelength-dependent efficiency as a next step before we demonstrate various experiments in undergraduate optics laboratories.

#### A. Measurement of DMD efficiency

At first, we start with the characterization of the DMD and measure the efficiency of the reflection for four commonly used wavelength spanning the whole visible range from near-UV to near-IR, i.e. 405 nm, 532 nm, 650 nm, and 808 nm. The experimental setup is shown in Fig. [Fig. 1](#) but replacing the camera with a power meter to measure the light before and after impinging on the DMD. We also adjust the beam sizes for all wavelength to be smaller than the screen, such that all light is reflected or modulated by the DMD.

In order to measure the efficiency of the DMD, the mirrors of the DMD must be unified into a single position. We chose to use the off position, i.e. we performed these measurements with the SLM switched off. In this configuration, the major losses stem from absorption and diffraction due to the pixels and limited fill-factor (space between the pixels) of the device. The efficiency is then obtained as the ratio

$$\epsilon = \frac{P_o}{P_r},$$  \hspace{1cm} (1)
where $P_r$ is the reference power or the power of the input beam falling on the DMD, and $P_o$ is the measured output power. As expected for a device designed as a projector, we find that the efficiency is slightly higher for light with a wavelength in the visible regime, i.e. 532 nm and 650 nm (see fig. 2 solid line). We find values of around 55-60 % for all tested wavelength. After this overall efficiency measurement, we then measured the diffraction efficiency for the zeroth and first diffraction orders when a binary grating with equally spaced on and off steps of 10 pixels is displayed. Again, we determine the efficiency as the measured power in the targeted diffraction orders $P_o$, isolated using an iris, with respect to the incoming beam. This diffraction efficiency should now be mainly determined by diffraction theory, i.e. we should obtain a theoretically maximal diffraction efficiency of 10.1 % in both first orders (neglecting losses). As required from the symmetry of binary gratings, we find very similar values for both first order diffractions. We further measure values between 2-6 %, which also matches the theoretical value very nicely if the overall efficiency determined above is accounted for. For the zeros order, i.e. the unmodulated light, we find around 6-16 %. As
before, we find the overall behaviour that the efficiency is reduced at the edges of the visible spectrum (see Fig. 2). From our measurements, we see that this DMD model has the best efficiency near 520-570 nm.

Hence, for the remaining set of experiments using the DMD, we used the green laser for which the DMD has the highest diffraction efficiency. Moreover, this wavelength seems to be the best fit for undergraduate laboratories and demonstrations, as the human eyes also are the most sensitive in this regime such that eye-safe low-power laser modules can be used.

B. Single- and multiple-slit diffraction

To showcase the advantage of using such a flexibly programmable SLM, we first investigate the diffraction of a laser beam through a single slit of varying width as well as an arrangement with an increasing number of slits.

To demonstrate the evolution of the intensity pattern obtained from a single slit diffraction of varying width, we change the slit widths from 28 pixels (211.68 µm) to 1 pixel (7.56 µm). We then use a lens placed one focal distance away from the DMD screen and observe the changing intensity patterns with a CMOS camera placed in the focal of the lens (2-f configuration). With this arrangement, we obtain the far-field intensity pattern of the diffracted light field. To demonstrate the evolution of the diffraction pattern, we display in Figure 3(a) the intensity profiles for 10 different slit widths. One nicely observes the transformation of the slit shadow image for a very wide slit to a widely diffracted profile known from very narrow slits.

In the case of a varying number of slits, we keep the experimental setup as it is and started with a single slit of ten pixels width (75.6 µm). We then increased the number of slits by one for each recording (distance between the slits is also set to 10 pixels). Because in the final arrangement the laser impinges on a region fully covered by slits, the diffraction can be considered equal to that of a grating. Similar as before, we recorded images for each setting and plot the intensity profiles across the maximum intensity in one graph (see Fig. 3(b)). From these measurements, one can nicely observe the relatively smooth transition from a single slit diffraction pattern to that of a double, triple and multiple-slit pattern. The higher the number the slits, the clearer the diffraction pattern of a binary grating appears.

Thus, the demonstrated set of measurements can be used in undergraduate optics lab-
FIG. 3. Intensity cross sections for different diffraction patterns. a) Decreasing the slit width displayed on the DMD from 211.68 µm (28 pixels) to 7.56 µm (1 pixel) leads to a broadening of the intensity pattern. b) By increasing the number of slits from 1 to 10, one can obtain a continuous change from diffraction through slits to a diffraction on a grating. The vertical-axis represents the normalized intensity recorded using a camera.

In undergraduate laboratories to show the effect of a varying slit as well as the number of slits with respect to the diffraction of light. In addition, the results can be related to an optical Fourier transformation, which we will explore in the following subsection in more detail.

C. Optical Fourier transformation

As mentioned earlier, another possible use for such an experiment in undergraduate laboratories is to perform an optical Fourier transform (FT). In order to demonstrate how the FT can be implemented, we used the logo of our university, Tampere University. First, the picture as a black and white image is displayed on the DMD. Then, we enlarge the beam to approximately 1 inch diameter that it is much larger than the DMD screen to ensure a near plane wave illumination of the SLM. After reflecting off the screen, only the ON pixels (white) reflect the beam into the desired direction towards the camera. To obtain a clear image of the image on the DMD, we build a 2f-2f imaging system, i.e. we placed the lens two focal lengths away from the DMD screen and the camera another two focal distances away from the lens. The utilized mask and the recorded image are shown in Fig. 4(a). After this initial test, we then place the lens and camera back to the positions preforming the
FIG. 4. Imaging and optical Fourier transformation using the DMD. a) Using a mask (here the Tamper University logo, see inset) and a 2f-2f imaging system, one can generate an image using the DMD. b) by implementing a lens in a 2-f configuration, one can perform an optical Fourier transformation (FT) of the image. The upper image shows the recorded intensity pattern, which nicely matches a calculated Fourier transform (lower left side) as well as the simulation of the experimental setup performing an optical FT (lower right side).

Fourier transformation (2-f configuration), i.e. only one focal distance between screen and lens as well as lens and camera. With this configuration, the recorded intensity structure of the light corresponds to the Fourier transform of the original image.

To verify the correctness of the obtained intensity pattern, we compare our measured FT with theoretical predictions. We do this by calculating the FT using a 2D fast Fourier transformation, e.g. using Matlab, as well as simulating our setup using a split-step beam propagation method to obtain the optical FT (see Fig. 4(b)). From the nice agreement with the theoretical FT, we see that indeed light passing through lens results in an intensity pattern corresponding to a FT. In addition, we see when we compare the results for the measured and simulated FT, that the agreement is even better. Thus from this latter comparison, we find that our setup works very well with only minor imperfection leading to slight discrepancies. On the other hand, the comparison of both, the measured and simulated FT with the calculated FT shows that while they match well, there is still a difference between the two operations.
After having investigated the possibilities to study optical Fourier transformations, we now turn to spatial amplitude modulations that result in beams with varying phase fronts.

D. Fresnel Zone plate

At first, we test the focusing effect using only amplitude modulations, i.e. we implement a so-called Fresnel zone plate (FZP). For this, we create the pattern of a FZP with a focal length of 10 cm, display it on the DMD, remove the lens from the optical setup, and keep the plane wave illumination. We now see that the beam focuses to a small spot after propagated to the focal plane. When placing our camera at that plane, however, we not only see that the beam is tightly focused to a Gaussian spot but also slightly deformed (see Fig 5). Because we ensure the circular symmetry of the cutout beam at the DMD by displaying the FZP only at a circular region, we relate this deformation to astigmatism of the DMD. This might stem from the imperfect optical flatness of the device due to the rather low production costs and can also be seen for other simple spatial light modulator based on DMDs.

E. Generation of spatial modes using holography

As a last demonstration, we utilized the DMD DLP2000 to generate transverse spatial modes, in particular so-called Laguerre-Gaussian (LG) modes or donut beams. These beams have attracted a large amount of attention over the last decades in various fields due to the
properties attached to the spatial structure\textsuperscript{3}\textsuperscript{15,18}. The main feature of LG beams is their screw-like phase structure, i.e. a twisted helical wavefront of the form $e^{i\ell \phi}$, where $\phi$ is the azimuthal coordinate and $\ell$ corresponds to the quantized integer orbital angular momentum (OAM) value\textsuperscript{18}, which can take on values as large as 10,010\textsuperscript{19}. Because of this twisted structure, the beams have a phase singularity along the optical axis, which then leads to an intensity null and, thus, a donut-like intensity pattern\textsuperscript{18}.

Since our DMD is only able to modulate the amplitude, we have to use holography techniques to imprint such helical phase structures, thereby, generating donut beams. These holograms correspond to diffraction gratings with dislocation at the optical axis, which resembles a fork structure, hence, the name forked-gratings\textsuperscript{20,21}. Depending on the strength of the dislocation one generates donut beams with different topological charges, i.e. helical wavefronts where the phase changes increases as single or multiple times to $2\pi$ along the azimuthal direction.

![FIG. 6. Beam shaping via forked diffraction gratings. We generated three different donut beams carrying 1 (left), 2 (center) and 5 (right) quanta of OAM. The insets show the utilized forked, diffraction gratings, which lead to donut shaped beams (upper row) in the both first diffraction orders. The lower row shows the intensities in the focal plane, where the beams get distorted heavily due to astigmatism on the DMD such that Hermite-Gaussian beam patterns appear.](image)

In our experiment, we use fork diffraction gratings of the topological charge of 1, 2 and 5 (see insets in Fig. 6), which will lead to donut beams carrying $1\hbar$, $2\hbar$ and $5\hbar$ of OAM per photon. To better observe the structure of the beams, we again implement a lens into the beams with a focal length of 25 cm. When putting the camera close but not exactly into the focal plane (approximately 5 cm away), we observe the expected donut-like intensity pattern in both first diffraction orders. We also see that the beam diameter increases when
larger topological charges are imprinted leading to an increased divergence of the beam \cite{22} (see Fig 6 upper row). If we now put the camera in the focal plane, we expect the same mode structure to appear. However due to the above-described astigmatism, we see that the structure resembles another well-know spatial mode, i.e. a Hermite Gaussian (HG) mode (see Fig 6 lower row). This can be explained by the fact that astigmatism resembles a focusing using a cylindrical lens, which is known to transform LG modes into HG modes \cite{23}.

On one hand, this confirms our observation made above, i.e. that the DMD causes astigmatism when modulating the light. On the other hand, we can take advantage of this effect and use it to verify the imprinted topological charge by simply counting the number of observed lobes and their orientation. We observed the same amount of lobes for both first diffraction orders and that the number of lobes agrees with the topological charge that we set out to imprint onto the beams, i.e. the OAM value minus one. We further see that the observed patterns in both first orders are orthogonally oriented, which proves that both beams are carrying opposite OAM values. Thus, we have verified that using the DMD enables the generation of transverse spatial modes of light, such as the donut-shaped LG modes.

IV. CONCLUSION

The use of a BeagleBone device together with DLP lightcrafter evaluation module is a very user-friendly device and money-saving technique of obtaining an SLM of acceptable quality for various educational purposes, e.g. their use in undergraduate laboratories for demonstrating instructive experiments. Although we described the procedure used to modify one particular model, other LightCrafter models from Texas Instruments can also be converted using the same process. We characterized the efficiency of the device towards different wavelengths in optical range for gaining maximum output. Finally, we demonstrated that such a setup is capable to study various experiments like diffraction, interference, Fourier transforms, Fresnel zone plate, and complex amplitude modulation to obtain e.g. Laguerre-Gauss beams. Thus, the SLM can be easily employed for graduate as well as undergraduate-level projects in phase shaping, holography, and optical control.
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Appendix A: switching off the LED

Using these commands, one can switch off the LEDs in the case of low-light operations:

```
i2 c set -y 0 0x15 0x00 0x00 i
i2 c set -y 0 0x15 0x01 0x00 i
i2 c set -y 0 0x15 0x02 0x00 i
i2 c set -y 0 0x15 0x03 0x00 i
i2 c set -y 0 0x15 0x04 0x00 i
```

The different numbers are meant for different colours with 0x00 going for green all the way to 0x04 going for red. The latest part 0x00 indicates whether the LED is ON or OFF. It can be switched by putting 0x01 instead of 0x00. This can also be done by using the LightCrafter-Display-GUI software.