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Abstract. Digital micromirror devices (DMDs) by their high-switching speed, stability, and repeatability are promising devices for fast, reconfigurable telecommunication switches. However, their binary mirror orientation is an issue for conventional redirection of a large number of incoming ports to a similarly large number of output fibers, like with analog micro-opto electro-mechanical systems. We are presenting here the use of the DMD as a diffraction-based optical switch, where Fourier diffraction patterns are used to steer the incoming beams to any output configuration. Fourier diffraction patterns are computer-generated holograms that structure the incoming light into any shape in the output plane. This way, the light from any fiber can be redirected to any position in the output plane. The incoming light can also be split to any positions in the output plane. This technique has the potential to make an "any-to-any," true nonblocking, optical switch with high-port count, solving some of the problems of the present technology.
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Subject terms: optical switch; Fourier hologram; diffraction; nonblocking.

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1 Introduction

Internet usage has exploded and is driving the need for increased telecommunication bandwidth. The annual international Internet traffic and bandwidth growth have been over 40% the last 4 years[1] and is expected to continue on this trendline for the foreseeable future. The introduction of mobile devices such as smart phones and tablet PCs have increased the number of IP connections exponentially.[2] New and bandwidth demanding applications such as cloud computing, videoconferencing, social media, online gaming, or video-on-demand rely on this high bandwidth to provide content from the data centers to the end users.

Fiber optics are used in data transmission because of their large bandwidth capacity and ease of multiplexing multiple data streams on the same fiber.[3] Historically, the bandwidth bottleneck has always been in the conversion from optics for data transfer to electronics for data manipulation and back to optics for transmission. This multistep conversion was needed to perform operations such as signal amplification and restoration, wavelength conversion, or data routing and switching. In order to improve the transmission bandwidth, various electronic components have been replaced by optical devices such as fiber amplifier, dense wavelength division multiplexer, and more recently optical switches based on micro-opto electro-mechanical systems (MOEMS).[4]

At the core of the fiber optics network, and increasingly appearing in massive data centers, optical switches redirect the output of one fiber to the input of another one, establishing a communication link between two points. The optical switch avoids the costly step of converting the signal to an electrical signal for switching operation and converting the electrical signal back to optical signal for transmission. The optical switch provides both reduced latency and improved reliability. The current technology for switches uses an array of analog micromirrors or MOEMS.[5] To change the configuration of the switch, the angles of the mirrors are adjusted to send the beam to a specific fiber via another pathway.

In MOEMS optical switches, mirror orientation needs to be extremely precise to avoid crosstalk between fibers, and mirror position needs to be stable over time to maintain the link from hours to years. A feedback loop is currently used in MOEMS to ensure both these functionalities, but it is energy costly, increasing the operation cost. Ideally, the reconfiguration of the switch must also happen in a very short time to prevent any loss of data and to minimize the latency of the connection. With MOEMS, this time is on the order of a millisecond. The reconfiguration time is limited by the resonance frequency of the micromirrors which is dictated by their mass.

Though digital micromirror devices (DMDs) might be considered as a particular type of MOEMS, they will be distinguished in this work by the fact that they are digital by nature and their mirrors can only take two states: tilted in one direction and in the opposite direction. Because of the stability of these two positions, DMDs can be reconfigured much faster than MOEMS that require a stabilizability feedback loop.

2 DMD Advantages

Considering the current technology of MOEMS, DMDs have significant advantages for optical switching application:

- While MOEMS are limited to 1 ms (1 kHz) for repositioning the mirrors, DMDs can routinely have their mirrors flipped in 50 μs (20 kHz).

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- Lighter mirrors in a DMD induce less stress on the hinges, making the DMD more robust and have an extended lifetime. The number of switches before failure is considerably increased.
- Lower electrical consumption. DMDs are bistable, while MOEMS need a feedback loop.
- The manufacturing process of DMDs is very well mastered by Texas Instruments, and several companies are offering these devices in different format, some are already optimized for telecommunication wavelengths.
- The price per DMD unit is lower than MOEMS.

The potential for DMDs is very well known within the telecommunication industry, and they have been investigated for optical switches in the past. However, that research focused on using the DMD as a reflective element, which dramatically complicates the architecture of the switch.[6,7] Indeed, contrary to their analog counterpart (MOEMS), DMD mirrors can only be oriented according to two directions: they are digital by nature. Using reflection principle will require an increased number of separated mirrors to redirect the light to the correct port.

Here, we propose a different approach that takes advantage of the DMD but where the light is redirected not by reflection but by diffraction. Diffraction is defined as the change of direction due to an aperture such as a slit. By carefully organizing the size and position of multiple apertures, the direction of the diffracted light can be finely tuned. Such an arrangement of apertures is referred to as a diffraction pattern, or hologram, and can be loaded as an image on the DMD. Light striking the DMD binary hologram will be redirected to the calculated pattern and enter the output fibers.

Using a hologram, the diffracted direction is not limited to just two directions, as with reflection on the DMD mirrors. The Fresnel equation can be used to determine the diffractive pattern needed to redirect (steer) the incident light to specific directions. This approach is truly nonblocking. Moreover, one incoming beam can be divided into different output directions, or different input beams can be combined together at a same location, making the switch very versatile.

In addition to the advantages of DMDs described above, the diffractive approach has also its own benefits:

- The number of ports that can be accessed with the diffraction pattern is very high. In our case, 40,000 distinctive points can be addressed.
- Since the light from the incoming fibers is spread over a larger area (diffractive pattern) than with the MOEMS (single mirror), there is no risk of optical damage or heat dissipation problem when using the DMD.
- The diffraction pattern can include an optical function, such as focusing, to simplify the light injection into the output fiber.
- The diffracted beam from the DMD can be split into several beams, allowing one to redirect a single source into multiple outputs. This cannot be done with a single-mirror MOEMS configuration.

3 DMD Characterization

To demonstrate the capabilities of the DMD as an optical switch for data communication, we assembled a testbed and characterized the diffractive properties of the DMD.

The DMD we used was provided by Texas Instruments, Dallas, Texas. It is the Digital Light Processing (DLP™) 4100 kit with a DMD chipset coating optimized in the IR around 1500 nm. The resolution is 1024×768 pixels (XGA) for a 0.7-in. size. Pixel size is 13.6 μm, and pixel angles are ± 12 deg. Fill factor is 91%.

Since DMD mirrors have only two states or tilt angles (± 12 deg), grayscale in imaging applications is achieved by temporal integration: the mirrors are flipped back and forth between the two positions, so light is modulated at the desired intensity. For a data transmission application, this artifice cannot be used, since it will modulate the intensity of the signal. So, the DMD should only display binary patterns to diffract the incident light.

3.1 *Image Formation in the Visible*

As presented in Fig. 1, the initial setup consisted of an expanded laser beam that covered the entire surface of the DMD chipset and a Fourier lens to focus the diffracted beam into an image. The diffraction pattern was loaded as a black and white image (binary) onto the DMD via the GUI interface. An example is shown in Fig. 2, where the Texas Instruments logo is transformed into a diffraction pattern and loaded as an image on the DMD chipset, to be reconstructed by the setup. Different diffraction orders are visible on Fig. 2(c), with the logo being the $+1$ and -1 orders, and the center spot the undiffracted light, or 0 (zero) order.

With that setup, we also demonstrated the possibility to steer different sources by using two lasers (a red helium neon and a blue diode-pumped solid-state laser), each one covering only half of the DMD chipset. Due to the large difference in wavelength (633 and 488 nm), the diffraction patterns have to be scaled to achieved the desired image. Figure 3 shows how the blue and red diffracted beams can be separated or mixed at will, just by changing the diffraction pattern. This same technique can be used in data switching to separate or to combine signals from different fibers.

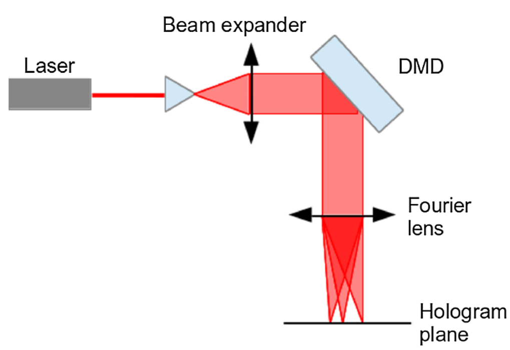

Fig. 1 Setup schematic. A laser beam is expanded to illuminate the entire digital micromirror device (DMD) chipset, and the diffracted image is focused by a Fourier lens.

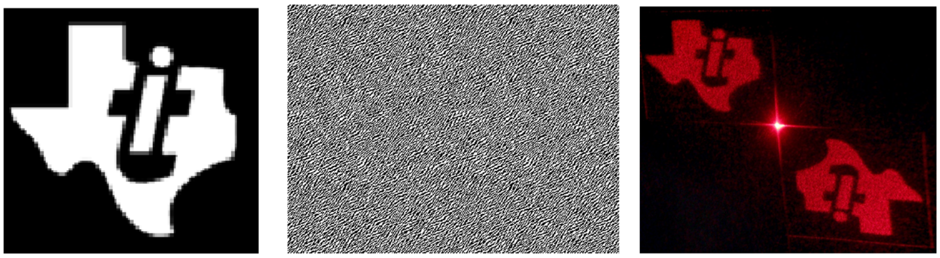

Fig. 2 Texas Instruments logo, diffraction pattern, and hologram as reconstructed by the setup.

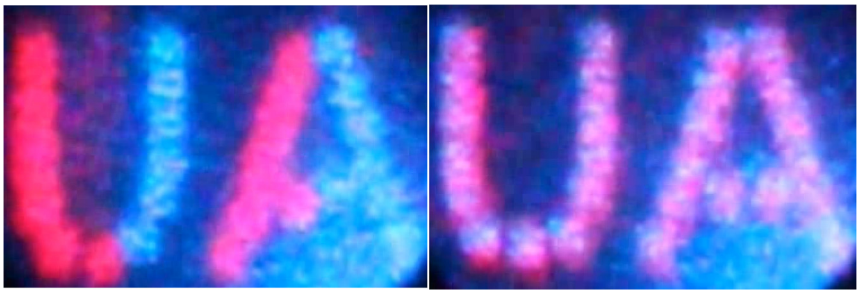

Fig. 3 Two colors-diffracted image showing the separation or mixing of the input sources.

3.2 *Characterization in the Infrared*

The angular separation between the zero and ±1 orders depends of the wavelength and is given by the grating equation

$$\sin(\theta_{\mathrm{i}}) \pm \sin(\theta_{\mathrm{d}}) = \frac{\lambda}{d}, \tag{1}$$

where θ_{i} is the angle of incidence, θ_{d} the diffraction angle, λ is the wavelength, and d is the size of the pattern.

When all the mirrors from the DMD are oriented in one direction (entirely in black or white image), d has the size of the DMD mirrors (i.e., 13.6 μm) giving a diffraction angle of 6.5 deg for the 1550-nm telecommunication C-band. For a 1-pixel checker pattern (every other pixel tilted in the opposite direction), the pattern separation between the diffraction planes is $\sqrt{2}d = 19.2\ \mu\text{m}$, and the distance between the orders is 4.6 deg. This diffraction angle is the largest that can be achieved and will determine the maximum separation between the fibers in an optical switch. Those angular values have been confirmed experimentally using a IR-fiber laser and a goniometric table.

An important parameter for an optical switch is the insertion loss: the optical power loss when the light passes through the switch. The insertion loss depends on several factors such as the quality of the optics used to collimate and inject the beam into the fiber, but will be directly proportional to the diffraction efficiency of the DMD. The efficiency depends on the wavelength and the light incidence angle on the DMD chipset. We measured the ratio of the diffracted light in the different orders according to the incident angle at 1550 nm. Since the mirrors on the DMD are tilting along a 45-deg axis according to the display edges, the incident angle has been measured according to mirror geometry, not to the display front window. In our setup, the plane of incidence coincides with the plane of rotation of the DMD mirrors. Figure 4 presents those results and shows that an entirely black (or white) pattern will reflect a maximum of 74% of the light at an angle of 24 deg, which is twice the mirror tilt. The remaining 26% of the light is scattered in many different orders because of the square structure of the mirrors themselves. When a diffraction pattern is loaded, a maximum of 9% of the light can be directed to the first order at an angle of 14 deg. This efficiency value is in accordance with the diffraction theory of binary absorption holograms that predicts a maximum of 10%.[8]

It is important to note that the maximum diffracted energy can be directed to different orders, like say (+1, +2) or (+2, +1), by changing the incident angle on the DMD, but never gets higher than the 9% measured at 14 deg.

To maximize the diffraction efficiency, we also measured the diffracted energy according to the cutoff graylevel used when converting the diffraction pattern into binary. Indeed, the diffraction pattern is initially calculated as a 256 grayscale image, and then converted into binary black and white images to be displayed by the DMD. In a perfectly symmetrical case, one would expect to have symmetrical curve and a peak efficiency at 50% black/white pixel ratio (i.e., 127 graylevel cutoff). However, Fig. 5 shows that the curve is asymmetrical and peaks around level 135 with 9.06% efficiency. This is due to the mirror cross-section that is larger when oriented toward the incident light rather than away from it, which breaks the symmetry. A diffraction pattern with more mirrors reflecting light toward the +1 order (cutoff level higher than 127) will direct more energy in that order, but too many mirrors oriented toward that direction (cutoff level higher than 135) reduces the diffraction efficiency, and so the energy in the +1 order is ultimately reduced.

In this particular configuration, the signal-to-noise ratio (background energy versus signal energy) has been measured to 50 dB, which is in part with telecommunication devices, and will define the crosstalk in a switch application. There was no filtration of the different orders, but we restricted the diffracted beam to an area far enough from the zero order to avoid scattered light. This reduces the number of addressable positions, but only by a marginal factor (2%). Filtration of the orders by an aperture located in a first image plane will further increase the SNR and reduce potential crosstalk between fibers.

4 Discussion

DMDs have several interesting features that make them very very attractive as data communication optical switches. Reconfiguration speed, reduced electrical consumption, and reliability are among them. We proved it is indeed possible to use diffraction patterns to redirect the light from incoming fibers to different locations, making the DMD a true, nonblocking optical switch with functions such as beam combiner and multiplexer that cannot be easily addressed with other technologies. However, the diffraction efficiency is rather poor with only 9%, limiting the injection loss to a minimum of −10.5 db. Amplification stages are always possible after switching, but this will also increase the noise and offset any electrical consumption gain.

The problem of the diffraction efficiency is not due to the device limitations such as mirror size, reflectivity, or fill factor. Rather, it is given by the diffraction theory of binary amplitude holograms that predict a maximum of 10% for this kind of structure, independently of the modulation device. Reducing further more, the mirror size will increase the maximum diffraction angle θ_d, which will have a positive impact on the number of fibers that can be addressed in the switch. But unfortunately, it will not increase the efficiency.

To increase the efficiency, the coupled wave theory of diffraction indicates that we should use a phase modulation rather than amplitude modulation. A binary phase modulation that reaches 2π has a maximum theoretical efficiency of 41%, and a multiple-levels phase hologram can reach 100%. This is the case of liquid crystal on silicon (LCOS) displays that have demonstrated numbers close to those predicted.[9] However, LCOS displays suffer some problems when used as an optical switch in data telecommunication: they are rather slow (200 Hz), they are polarization sensitive, and their power consumption is relatively high.

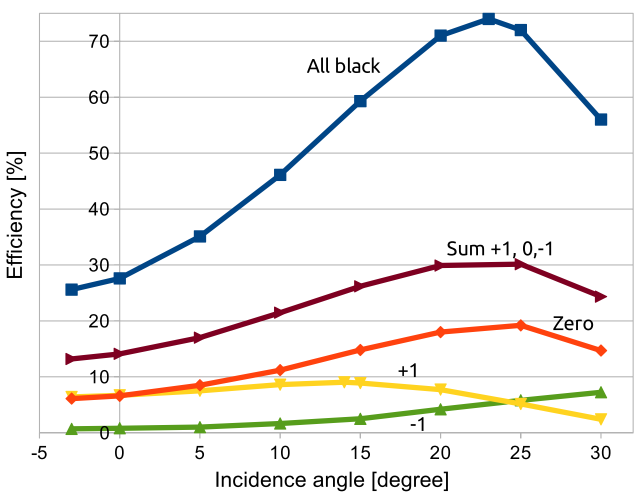

Fig. 4 Diffraction efficiency of the different orders at 1550 nm, according to the incident angle.

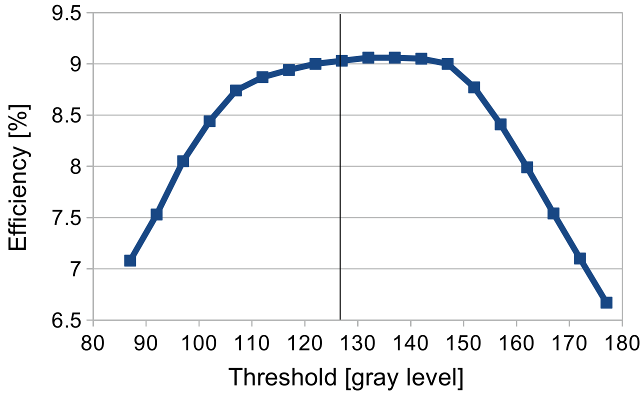

Fig. 5 Diffraction efficiency of the +1 order at 14 deg, according to the threshold level used to convert the diffraction pattern from grayscale to binary. Note the asymmetry.

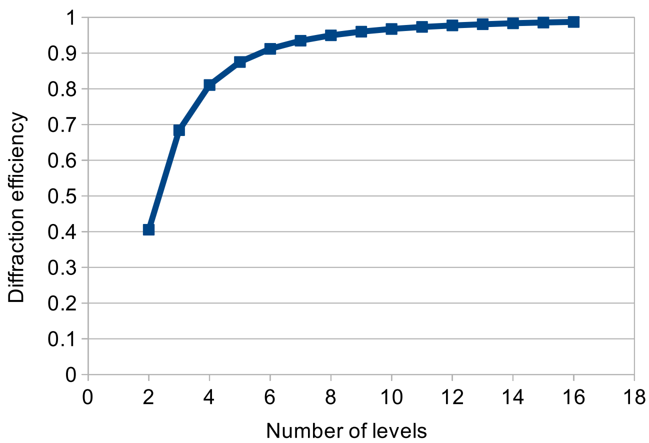

Fig. 6 Diffraction efficiency according to the number of phase levels.

A more efficient solution would be to have a piston MOEMS, such as those described by Bifano[10] or Lopez et al.,[11] with the mirrors able to shift by a distance of π (775 nm), the back and forth light path making for the 2π phase shift. With such a system, a very limited number of levels (Z) will be necessary to have large efficiency, as it is given by Eq. (2) and plotted in Fig. 6.[12,13]

$$\eta = \mathrm{sinc}(1/Z)^2. \tag{2}$$

In our future work, we will continue to investigate the possibility to use diffraction patterns to make a data communication optical switch. The next step will be to integrate the optical train from fibers to fibers to have a demonstrator that can be tested on telecommunication equipment. Even though the optical loss of the switch might be too high for the moment because of the DMD diffraction efficiency, this type of technology can work indifferently with phase modulator devices that bear the promise of very high efficiency, while keeping the same sort of advantages.

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