Spatially resolved contrast measurement of diffractive micromirror arrays

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ABSTRACT

Diffractive micromirror arrays (MMA) are a special class of optical MEMS, serving as spatial light modulators (SLM) that control the phase of reflected light. Since the surface profile is the determining factor for an accurate phase modulation, high-precision topographic characterization techniques are essential to reach highest optical performance. While optical profiling techniques such as white-light interferometry are still considered to be most suitable to this task, the practical limits of interferometric techniques start to become apparent with the current state of optical MEMS technology. Light scatter from structured surfaces carries information about their topography, making scatter techniques a promising alternative. Therefore, a spatially resolved scatter measurement technique, which takes advantage of the MMA’s diffractive principle, has been implemented experimentally. Spectral measurements show very high contrast ratios (up to 10,000 in selected samples), which are consistent with calculations from micromirror roughness parameters obtained by white-light interferometry, and demonstrate a high sensitivity to changes in the surface topography. The technique thus seems promising for the fast and highly sensitive characterization of diffractive MMAs.

Keywords: diffractive MEMS, MOEMS, spatial light modulator, MMA, characterization, display contrast, Fourier optics, scattered light

1. INTRODUCTION

Torsional, diffractive micromirror arrays (MMA) are a special class of reflective micro-electro-mechanical systems (MEMS) that provide a programmable, continuous control of the phase of light, and therefore serve as spatial light modulators - SLM (Figure 1). Compared to conventional SLMs such as LCD, LCOS or DMD, their main features are a highly precise analog phase control, high-speed capabilities in the 1…1000 kHz range and particularly a broad modulation spectrum from the deep UV to the IR. Applications can be found e.g. in deep UV mask writing [1], laser direct imaging [2], and optical microscopy with spatio-angular illumination control [3]. Driven by lithographic applications, there is a permanent need for ever increasing optical performance of MEMS modulators, with primary focus on highest accuracy of the phase modulation.

In order to meet this trend, from the developer’s perspective two strategies are to be mentioned here: Firstly, the MEMS technology is continuously developed with process innovations, outlined in earlier publications [4]–[7]. Secondly, as complementary approach, the careful qualification and individual optimization of each single MEMS device may support highest optical performance. For example, a profilometric calibration of each micromirror’s deflection characteristics is routinely performed to achieve a deflection accuracy as low as a few nanometers [8].
We study a novel characterization approach for diffractive MMAs that relies on intensity-based measures rather than interferometric principles. It is based on a spatially resolved measurement of scattered light from the MMA surface. Compared to interferometric techniques, which measure a phase shift with respect to a reference wave, an intensity-based approach is much less prone to mechanical vibrations and drifts, and in principle offers the possibility to scale the measurement range by adjusting the illumination intensity, e.g. with the help of filters.

As a specific example of such an approach, a spatially resolved contrast measurement was implemented, which illustrates the distinct opportunities that may arise from the combination of spatially resolved scattering methods with the MMA’s diffractive operation principle. The concept of the measurement technique and our definition of a contrast ratio are introduced in the next section, followed by an overview of the practical implementation and a discussion of some key aspects of the experimental work. Finally, typical results of spectral contrast measurements are presented and discussed for their consistency with estimations based on established surface roughness parameters.

## 2. MEASUREMENT CONCEPT

Light scatter from structured surfaces carries valuable information about their topographic properties; therefore scatter measurements are used as fast, noncontact, versatile instruments in both scientific and industrial environments, e.g. in the optics, semiconductor, and paper industries for surface roughness measurements or the detection of particles and contaminations. Since the phase accuracy of diffractive MMAs is determined by their surface shape, the study of surface scatter appears as an attractive approach for MMA characterization [9]. The application of scatter techniques to diffractive MMAs is, however, not straightforward since samples of scatter measurements typically are supposed to be rather smooth or “unpatterned”, whereas MMAs consist of a regular grid of micron-sized elements with abrupt surface height changes at the micromirror edges, leading to strong diffraction effects. Additionally, there is a need for a high spatial resolution in order to investigate varying characteristics across the surface. The two main challenges are thus a) the separation of the scatter signal from the diffraction effects and b) the recovery of spatial scatter information.

### 2.1 Optical properties of diffractive MMAs

MMAs act as phase gratings, where monochromatic light is being diffracted into distinct directions that are determined by the mirror pitch and the wavelength according to the grating equation (inset of Figure 2). The intensity in the so-called diffraction orders is mainly determined by the deflection state of the individual micromirrors (here supposed to be the same for the whole mirror array). The deflection $d$ is being defined as the distance of the micromirror edge that is parallel to the rotation axis to its untilted position (see inset of Figure 2). To illustrate this relationship, the intensity in the 0th diffraction order, i.e. the specular direction, is shown as a function of deflection in Figure 2 for an ideal MMA. Here, “ideal” means an MMA consisting of perfectly flat, smooth micromirrors with exact deflections and a 100 % fill factor. Two special cases are important for the following discussion: When all micromirrors are untilted ($d = 0$), the MMA basically acts as a plane mirror, reflecting the maximum of light in the specular direction. If all micromirrors are deflected to a multiple of a quarter of the wavelength ($d = n\lambda/4$), the MMA forms a blazed grating and diffracts all the light into a single higher diffraction order yielding zero intensity in the specular direction.
2.2 Separation of diffraction and scatter

For real MMAs, any deviation from the ideal profile such as micromirror surface corrugations result in light scatter (Figure 3), which superimposes the diffraction pattern of an ideal MMA. For clarity, from here on we use the terms “diffraction” and “scatter” to distinguish between the diffraction contributions of an ideal MMA (as defined in the previous section) and the additional scatter contributions due to surface imperfections, respectively. This choice of terms reflects our experimental interest, i.e. to separate scatter from diffraction signals of an ideal MMA; since only the scattered light carries information about the MMA’s surface imperfections.

The general idea to realize this separation in practice is to choose appropriate micromirror tilt angles to suppress the intensity in certain diffraction orders. For example, the diffraction contribution in the specular direction (0th diffraction order) vanishes when the MMA fulfills the blaze condition $d = n\lambda/4$ as discussed above (see e.g. Figure 2).

2.3 Principle of spatially resolved scatter measurements

In a typical scatter measurement (Figure 4 a), a detector measures the intensity $dP_s$ that is scattered (or diffracted) by the sample into a certain solid angle $d\Omega_s$ around the angle $\theta_s$. By scanning over all scatter angles, the so-called power spectral density (PSD) of the surface can be measured [9]. In a Fourier optics description, the decomposition of the surface profile into its spatial frequency components corresponds to diffraction into certain angles and can be mathematically described by a Fourier transform of the surface profile in position space to the light field in the spatial
frequency space. It is, however, not possible to localize features in position space from the PSD since the phase information of the scattered light field is lost in the measurement process.

To recover the phase information, the well-known property of a simple lens (or mirror) to perform a (second) Fourier transform between the two conjugate focal planes, can be exploited. Two lenses in a 4f arrangement may be used to provide the required transformation back into position space (Figure 4 b). A so-called “Fourier” aperture is positioned in the intermediate focal plane, i.e. the spatial frequency space, and serves two purposes: First, it enables the separation of scatter and diffraction when the MMA is driven as a blazed grating as discussed in the previous section. Secondly, it enables paraxial imaging in a well-defined aperture range.

From another perspective, the setup in Figure 4 b is similar to a conventional dark field microscope, where a specimen is illuminated obliquely, the direct light, i.e. the 0th diffraction order, is being blocked and only the scattered light in a certain direction is gathered by the imaging optics. Our approach is slightly different in that we illuminate normally and are able to “reroute” the 0th diffraction order out of the imaging path by choosing an appropriate micromirror deflection.

In principle, one could measure the scatter in any direction by realigning the detection optics and choosing a suitable micromirror deflection to minimize diffraction in the chosen direction; but the 0th diffraction order offers the unique advantage of being achromatic and thus enabling multispectral measurements without any change in the geometry of the setup. Furthermore, in this configuration it is easy to perform relative measurements by using the MMA with zero tilt as a reference to eliminate the influence of illumination intensity, exposure time, fill factor, overall MMA reflectivity, and camera sensitivity.

From a device perspective, such a relative scatter measurement corresponds to two basic MMA states: The highest possible intensity is reflected into the specular direction when the micromirrors are untilted and the lowest when it forms a blazed grating (refer to Figure 2). The ratio of the intensities measured for these two settings can thus be understood as a full-on/full-off contrast ratio and since the individual measurements are images that provide spatial resolution, it can be calculated across the whole MMA surface leading to a so-called “contrast map”. The reciprocal of the contrast ratio
corresponds to the relative scatter measurement described above, so one might equivalently choose a contrast map or a (relative) scatter map for analysis. The relations between the two terms might be illustrated in the following way:

\[
\text{contrast ratio} \equiv \frac{I_{\text{max}}}{I_{\text{min}}} = \frac{I(\text{untilted})}{I(\text{blazed})} = \frac{\text{reference scatter}}{\text{relative scatter}} = 1
\]  

(1)

3. EXPERIMENTAL WORK

3.1 System setup

The experimental implementation is based upon an existing characterization setup for diffractive MMAs (Figure 5) [10],[11]. The setup with reflective optics comprises five laser sources in the spectral range 248–830 nm, a beam shaping and homogenization optics, and a detection optics. The effect of the 4f arrangement to provide a transform back into position space as discussed in the previous section (Figure 4 b) is here achieved with only one spherical mirror and an aperture placed in its focal plane. The focal length of the mirror and the distances between the optical elements are chosen such as to match the magnification to the dimensions of the MMA and the detector. As spatial light detector a charge-coupled device (CCD) camera with a 16bit analog-to-digital (A/D) converter is employed (Finger Lake Instruments ML-1603-2-LUM with Kodak KAF-1603 sensor with 1536 x 1024 pixels and Lumogen-coating). The illumination power can be adjusted by neutral density filters to “reposition” the signal within the camera’s dynamic range, which can be used to effectively increase the dynamic range of the whole setup.

The key tasks necessary to create a spatially resolved contrast measurement are a careful consideration of the CCD nonlinearity, a systematic stray light reduction, and the development of automated measurement and image processing routines.

![Figure 5: Sketch of the multispectral, reflective measurement setup; adapted from [10].](image)

3.2 CCD nonlinearity

Measuring both high and low light intensities with one detector (according to the MMA modulation states), requires that an important feature of the detector, its “linearity”, is well known in a reasonable dynamic range of at least 3 to 4 orders of magnitude. I.e. it is necessary to know the proportionality between the number of incident photons and the measurement signal when all other parameters (wavelength, temperature, etc.) are held constant.

Modern, scientific CCD cameras, whose A/D conversion electronics are attuned to the linear part of the CCD transfer curve, i.e. avoiding the saturation region of the CCD, are highly linear devices. The nonlinearity stated by some manufacturers is usually in the range of a few percent or below. However, since this measure of nonlinearity is derived from the maximal deviations from a linear camera response divided by the highest signal [12], it is biased towards higher signal levels and the impact of the detector nonlinearity on measurements at low light levels can thus hardly be estimated. Therefore, we decided to characterize our camera’s nonlinearity within the first experimental step. For that purpose the MMA is replaced by a mirror and the (stabilized) laser sources are driven in cw mode to provide a constant intensity at the camera. A series of measurements with varying exposure times \( t \) is performed to scan across the camera’s dynamic range and a linear fit of the data is done. Additionally, the offset between the theoretical and effective exposure
time is corrected for as well. The measured signal $S_{\text{meas}}$ is then divided by the linear signal $S_{\text{lin}}$, which would be measured if the detector would be perfectly linear (Figure 6). In line with [13], we call this ratio “relative gain” and plot it against the measured signal to be able to compare measurements with different intensities.

**Figure 6:** Principle of CCD nonlinearity measurement. The exposure time is varied with constant intensity to sweep over the whole signal range of the camera (e.g. 0–65535 for 16bit). A linear fit represents a detector with perfect linearity and is used as reference $S_{\text{lin}}$. For each measured signal $S_{\text{meas}}$ the relative gain provides a measure for the nonlinearity at this particular signal level. (Here, the measured signal $S_{\text{meas}}$ is supposed be free of random errors, exclusively representing the systematic error due to the detector nonlinearity.)

We measured the relative gain of our camera, which shows a monotonic decrease towards lower signal levels (Figure 7). The relative gain is $>0.95$ above 3000 counts corresponding to a nonlinearity error $<5\%$, but drops to about 0.75 for the lowest measured signal levels around 50 counts, meaning that the camera there only displays about 75\% of the “true” signal. We found the relative gain to be wavelength-independent (from 405 to 830 nm) and reproducible in repeated measurements. Given that the relative gain only depends on the signal level, the relative gain for a given signal $S_{\text{meas}}$ can be used to correct for the nonlinearity. A fit of the measured relative gain data is used for this correction (solid line in Figure 7).

**Figure 7:** Relative gain measurements of the employed 16bit CCD camera for three different wavelengths and fit (solid line) used for the nonlinearity correction.
### 3.3 Stray light reduction

We consider stray light as all light impinging on the camera chip which did not come from the active MMA area through the spatial filter. Sources of stray light might be ambient light sources, such as laboratory lighting, PC monitors, status LEDs (first kind), or the laser source used for illuminating the MMA itself (second kind), which is much harder to control, since it cannot be easily blocked at the source.

Most stray light of the first kind is blocked by an opaque housing which surrounds almost all of the setup. However, additional baffles are needed to block the light e.g. from the status LEDs of the MMA control board, which has to remain close to the MMA device inside the housing. Stray light of the second kind results both from scattering at optical components such as mirrors, apertures, and passive MMA structures and non-optical components such as posts, mounts, the optical table, and the housing. According to the experiments, the decisive measure to reduce stray light is to tailor the illuminated area to just the active MMA region (avoiding scatter from surrounding structures). An adjustable slit right in front of the MMA serves that purpose.

### 3.4 Measurement automation and image processing

The diffractive MMAs have been designed for pulsed operation and the laser sources are synchronized with the MMA actuation cycle, so that several pulses are integrated on the CCD chip within the exposure time. A self-written LabVIEW program running on a PC controls this pulsed operation and synchronization of the MMA, the laser sources, and the CCD camera and is also used to perform automated measurement and analysis tasks.

To perform a contrast measurement (Figure 8), multiple exposures are acquired for both deflection settings (blazed & untilted) and fed to an image processing routine. (1) An average image is calculated from $N$ exposures to average out the jitter in the exposure time (introduced by the mechanical shutter) and to reduce the pixel noise by a factor of $1/\sqrt{N}$. (2) A spatial averaging over a $M \times M$ neighborhood around each pixel further reduces the noise by a factor of $1/M$ and inherently reduces the spatial resolution. Nevertheless, with a micromirror pitch of 16 μm the image consists of about $3.5 \times 3.5$ CCD pixels per micromirror in the current configuration and since the spatial resolution is limited by the Fourier aperture to less than the mirror pitch, no information is lost e.g. by a $3 \times 3$ spatial averaging. (3) An (average) bias image, i.e. the A/D converter offset, is then subtracted to get physically meaningful measurement values. If the signal level is very low, negative pixel values, which cannot be interpreted physically, can occur due to pixel noise and
may lead to strong artifacts in the subsequent scatter or contrast analysis. The main purpose of the initial averaging steps is therefore to minimize the number of these negative pixel values. (4) The nonlinearity correction is straightforwardly performed by dividing each pixel value by the respective relative gain (see Figure 7). Since the relative gain is not defined for negative values, the correction cannot be performed for the aforementioned pixels with negative values, resulting in undefined pixel values (NaN). (5) These NaNs are replaced by the median of the surrounding pixels to enable further processing. It should be noted that setting these pixels e.g. to a value of zero would be an inappropriate choice, skewing any analysis which is based on further averaging. This is most notable in the case of a contrast map where such pixels would have an infinite contrast. (6) An optional secondary spatial averaging further reduces image noise. The image processing is done by a macro for the free and open-source “Fiji” image processing package (Fiji Is Just ImageJ) [14], but was also transferred to LabVIEW recently.

4. EXPERIMENTAL RESULTS AND DISCUSSION
Spectral contrast measurements for several MMAs of the latest device generation for optogenetics [15] were performed, where the individual micromirror deflections have been adjusted to precisely fulfill the blaze condition. The measurements show generally very high contrast ratios in the range of a few hundreds to thousands, reaching as high as 10 000 and above for some devices. As an example, the contrast map of a device with particular high contrast ratios is shown in Figure 9 a. This is not only a certainly interesting device property, but also clearly shows the suitable dynamic range of the spatially resolved scatter measurement with more than four orders of magnitude. In addition to that fact, the “contrast map” of the same device is shown in Figure 9 b with a small offset of the deflections with respect to the optimum, which demonstrates the very high sensitivity of the contrast ratio to subtle changes in the surface topography.

![Figure 9](image-url)

Figure 9: (a) Contrast map of a MMA device with a particular high contrast at an illumination wavelength of 532 nm (256 x 256 micromirrors with a pitch of 16 μm), (b) “Contrast map” of the same device where the deflections were offset by 0.5 nm for the whole array, (c) Smoothed section profiles from upper left to lower right MMA corner.

The unprecedentedly high contrast ratios prompted us to check the consistency of our measurement results. To this end, we estimated the expected contrast ratios based on the micromirror surface roughness, which is known to be a determining factor for the MMA contrast [16]. In general, surface corrugations induce an upper contrast limit, which scales quadratically with the wavelength because of the underlying process of surface scattering [9]. However, as a central result of the studies performed earlier, only a single spatial frequency component of the surface corrugation determines the contrast limit. Here, this spatial frequency component is represented by the surface parameter \(a_1\), corresponding to the peak-to-valley amplitude of the surface corrugations at the mirror pitch frequency and yielding for the surface scatter-limited contrast ratio [16]:

\[
C_{max} \approx \left( \frac{\pi a_1}{\lambda} \right)^{-2}
\]

(2)

This parameter is routinely measured for each MMA device by white-light interferometry and might therefore serve as a starting point to estimate the wavelength-dependent contrast ratio. Since the measurement setup was designed with multispectral measurement capabilities we can vary both \(a_1\), by choosing MMA devices with varying surface roughness, and \(\lambda\), by switching between the five light sources in the range 248–830 nm.
The results of the spectral contrast measurements for two typical MMA devices and the contrast estimations calculated from the respective values of $a_1$ with equation (2) are shown in Figure 10. For these measurements the contrast map was derived from scans over different nominal deflection settings instead of the individually optimized actuation of all micromirrors. It could be shown, however, that this simpler method produces equivalent results. Sample A has a very shallow surface corrugation resulting in contrast ratios above 10,000 at higher wavelengths while sample B has stronger surface corrugations (corresponding to a higher $a_1$ value) leading to an expected contrast ratio below 2000 for the whole spectral range. This shows that the very high contrast is to be expected with the current state of the MMA technology in terms of micromirror roughness. Generally, the measured data fits well to the estimations, which underpins the plausibility of the present data. Latest experiment also indicate that additional factors come into play for distinct sample tests, which will be subject for future analysis.

![Figure 10: Spectral contrast measurements of two typical MMA devices.](image)

**5. CONCLUSIONS**

We studied a new principle for the characterization of the surface topography of diffractive MMAs that is based on the spatially resolved measurement of scattered light. The experimental setup has been successfully adapted for an extended dynamic range of 4 orders of magnitude with a minimized stray light level and an appropriate noise reduction together with a physically defined signal reference. The intensity-based approach is fast (since the whole device can be measured at once), provides a spatial resolution close to the mirror pitch, takes advantage of additional spectral information, and proves to be very sensitive to the surface topography. Measurements reveal very high MMA contrast ratios up to 10,000 in selected samples and are consistent with calculations from micromirror roughness parameters obtained by white-light interferometry. We conclude that the new measurement principle is ready for the quantitative analysis of diffractive MEMS. At this stage, it already illustrates the dominant contribution of micromirror surface corrugations to the MMA contrast. Further analysis of spatial MMA features is our next interest.

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REFERENCES


