Calibration of diffractive micromirror arrays for microscopy applications

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ABSTRACT

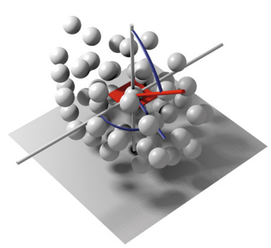
We report on our investigation to precisely actuate diffractive micromirror arrays (MMA) with an accuracy of λ/100. The test samples consist of analog, torsional MEMS arrays with 65 536 (256x256) mirror elements. These light modulators were developed for structured illumination purposes to be applied as programmable mask for life science and semiconductor microscopy application. Main part of the work relies on the well known characterization of MEMS mirrors with profilometry to automatically measure and approximate the MMA actuation state with high resolution. Examples illustrate the potential of this strategy to control the tilt state of many thousand micromirrors within the accuracy range of the characterization tool. In a dynamic range between 0 and >250 nm the MMA deflection has been precisely adjusted for final MMA application in the deep-UV - VIS - NIR spectral range. The optical properties of calibrated MMAs are tested in a laser measurement setup. After MMA calibration an increased homogeneity and improved image contrast are demonstrated for various illumination patterns.

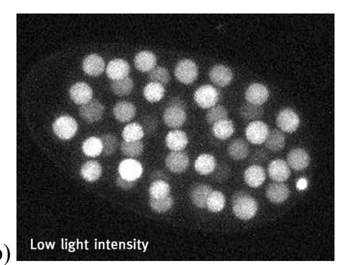
Keywords: micromirror array, microscopy, calibration, SLM, MMA, diffractive MMA

1. INTRODUCTION

Diffractive micromirror arrays (MMA) with quasi-continuous ("analog") actuator deflection are a special group of optical MEMS (micro-electro-mechanical systems). Compared to other spatial light modulators like digital mirror devices, scanning or membrane mirrors known from projection display systems [1], or adaptive optics [2], diffractive MMAs realize with their quasi-continuous deflection capability and highly integrated individual actuators a programmable phase mask of high efficiency. This concept allows, together with a Fourier-optical imaging system, the generation of grayscale patterns without the need for time- multiplexing, i.e. at high frame rate. These features have already led to the application as pattern generating device in photolithographic mask writers [3].

Recently, the field of high resolution microscopy called for light modulator elements to substitute classical static shadow masks in order to enhance system performance [4]. Focus here is the capability to adaptively illuminate several object scenarios, i.e. a programmable "structured illumination", to enhance the optical system resolution. This opens new application fields in semiconductor metrology and in live cell fluorescence microscopy, due to the enhancement of the visual quality of metrology targets and the reduction of photobleaching and light induced toxicity effects.

a) 

b) 

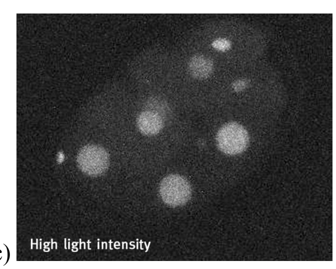
c) 

Figure 1: MMA application in live cell fluorescence microscopy. Left image (a) sketches the variable angular and spatial illumination of a 3D assembly of cells. Results of different illumination conditions are show on images (b) and (c). With steered illumination, interesting specimen parts become oberservable indicating the successful exclusion or presence of photo toxicity. [4], [5] (courtesy of Martin Kielhorn and Jean-Yves Tinevez)

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An application example of Life Science, recently published by King's College London, Institut Pasteur and In-Vision [4] [5], is illustrated in Figure 1. An example of illumination condition influence onto a 3D composition of live cells (a) is shown on images (b) and (c). Different light intensities affect the development of live cells, high intensities in (c) have impaired the growth. Variable illumination, where only the interesting parts of the cellular ensemble are illuminated, should avoid light induced effects to other specimen parts.

Driven by the application-specific requirements of microscope systems, a customer specific light modulator based on a micromirror array has been developed within the MEMI consortium over the past 3 years [4]. The modulation principle of diffractive MMAs was selected in order to reach the performance parameters required for flexible illumination control. The main arguments are properties like real-time grayscale imaging at high-speed as well as high contrast operation within an extended wavelength range. Previously, some of these properties have been analyzed with focus on device technology and optical characterization [6], [7]. The present paper studies the steps, necessary to achieve the high contrast capabilities of a programmable, diffractive light modulator.

Diffractive MEMS serve for the precise control of the phase of light - within a fraction of the optical wavelength. A relatively high accuracy is therefore necessary to realize their proper operation. Taking into account that diffractive MEMS usually comprise thousands or even millions of micromirrors for one single device [3] specialized characterization routines are usually applied that correct for technology variations by just measuring the precise state after manufacturing each single MEMS actuator. The present article gives a short overview about the current MMA development with special focus on the so called "calibration" procedure. In the first part, the MEMS test principle will be sketched. The procedure starts with the automatic determination of mirror deflections by means of a profilometric measurement system for various mirror driving voltages. The measured response curve is expressed afterwards with an analytic function for every individual mirror. The subsequent discussion illustrates changes within the illumination uniformity and high contrast operation as accuracy improvements of mirror control.

2. ANALOG MICROMIRROR ARRAYS AND THEIR APPLICATION AS PROGRAMMABLE PHASE MASK

The MMA modulator consists of 65 536 torsion elements, monolithically integrated onto a CMOS backplane [6] (see Figure 2). The 256 x 256 actuator elements in the active area ensure a fill factor greater than 90 % with a pitch of 16 µm and 0.5 µm slit width. Electrodes underneath the mirror plates enable the individual control of mirrors by applying addressing voltages in a range from 0 to 26 V (10 Bit resolution) with frame rates up to 1 kHz.

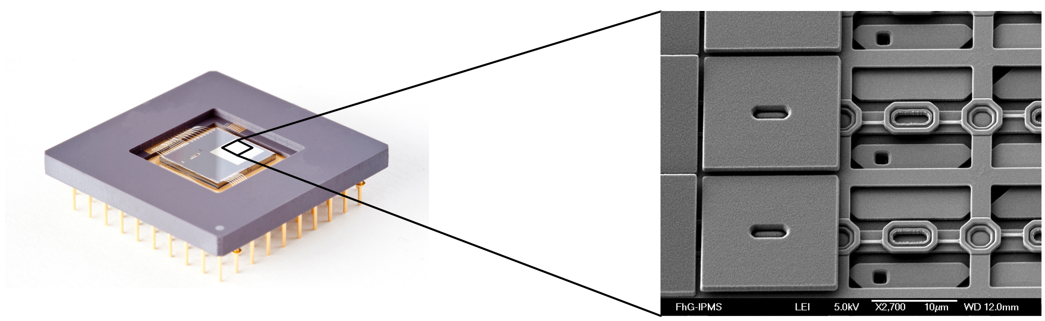

Figure 2: MMA sample for microscopy applications with ceramic chip package (left side). The sectioned view (right side) shows a SEM image of the 16 µm pitch micromirrors. Two slightly tilted mirror plates indicate the axis of torsion. Some of the mirror plates are removed in part of the image to illustrate the mechanical and electrical assembly underneath.

The potential difference between mirror plate and bottom electrode generates the electrostatic forces that - balanced by mechanical spring force - finally tilt the mirror plate to a distinct angle. Ruling parameter for the diffractive MMA operation is not directly the mirror's tilt angle but the so called edge deflection of the micromirrors as illustrated in Figure 3. The ratio of edge deflection and the wavelength of the incident light determines the diffractive response of the MMA device, where the quarter wave spacing marks the deflection distance of interest for the generation of prominent diffraction effects. The desired spectral MMA modulation in the range from deep UV to NIR consequently requires a mirror edge deflection above 200 nm to enable the modulation up to NIR wavelengths.

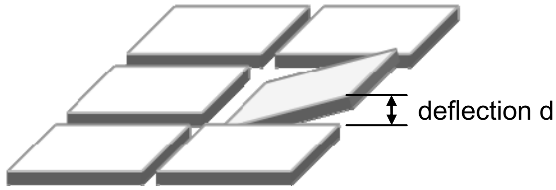

Figure 3: Sketch of a small mirror array. The mirror's deflection is expressed as the step height at the mirror edge with respect to the "non-tilted" or plane state.

Torsional micromirror arrays are programmable, diffractive optical elements that may be used with additional optics as contrast generating devices or so called programmable intensity masks. Desired illumination patterns are achieved with the MMA and a given laser source by utilization of an appropriate spatial filter (zero order operation in the pupil plane) that converts the phase information of the MMA into an intensity modulation. Intermediate MMA deflection states generate well defined transition intensities (gray values). In every case, the mirror array surface itself acts as a variable phase grating. The incident wave will be distributed into various diffraction orders, depending on the mirror deflection topography. The Fourier aperture or spatial filter (circular or rectangular aperture) transmits the zero diffraction contributions, blocks all higher orders, and finally transforms the lateral MMA pattern into an illumination profile in the image plane. As example, Figure 4 sketches a setup of optical components to realize the transformation of MMA phase information into intensity patterns for zero order operation.

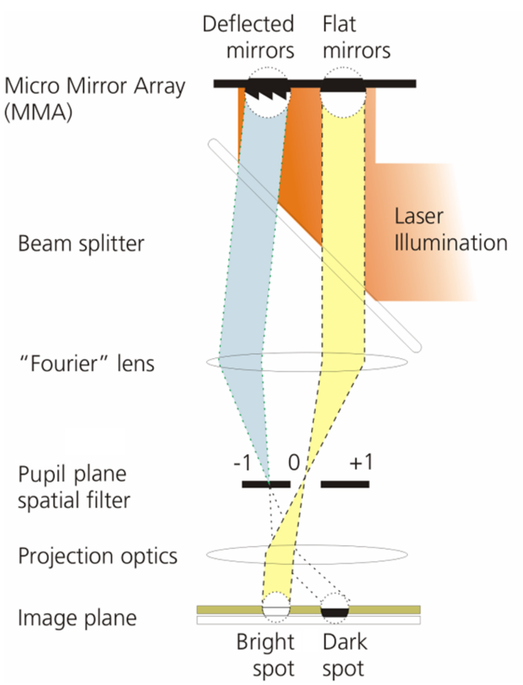

Figure 4: Optical application principle for diffractive MMAs. The blocking of higher diffraction orders in the pupil plane, induced by tilted mirrors, creates low intensity structures in the image plane.

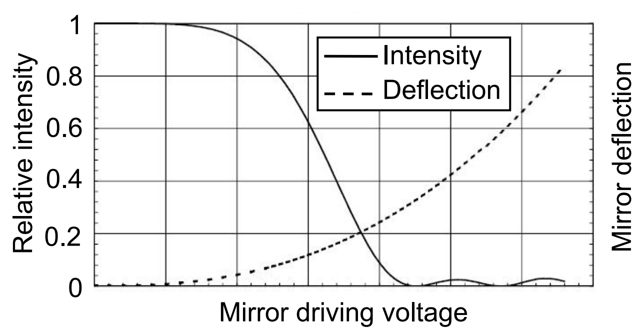

Figure 5: Image intensity and mirror deflection as a function of driving voltage.

The relation between image intensity I, mirror deflection d and laser illumination wavelength λ determines the simple formula [8], [9]:

$$I \propto \mathrm{sinc}^2\left(\frac{4\pi}{\lambda} d\right). \tag{1}$$

The image intensity is coupled to the mirror driving voltage through the electrostatic mirror deflection. Typical optical and mechanical responses to the driving voltage are illustrated in Figure 5. This nonlinear correlation between all the three variables has to be taken into account when grayscale patterns are to be generated.

3. MMA CALIBRATION CONCEPT

Micromirror arrays are manufactured by a sequence of micromachining processes. Typically the number of technology steps (like alternating etching, coating, lithography etc.) is very high. This generally results in a spread of mirror deflections and spring characteristics that directly enter into the optical device performance, bearing in mind the diffractive device operation on the nanometer scale.

In order to further enhance the optical performance, MEMS micromachining processes can be advantageously complemented with specialized characterization routines that directly reach the desired optical functionality by just measuring the precise state after manufacture of each single MEMS actuator. Such a goal is usually referred to as device calibration. Relevant procedures for diffractive MMA control have been published in the past ([10] - [13]). All have in common that mainly monochromatic applications have been in focus. These works consider the optical response of diffractive MMAs in a certain image plane for the data measurement or include specialized shearing interferometric measurements for the wavelength adjustment.

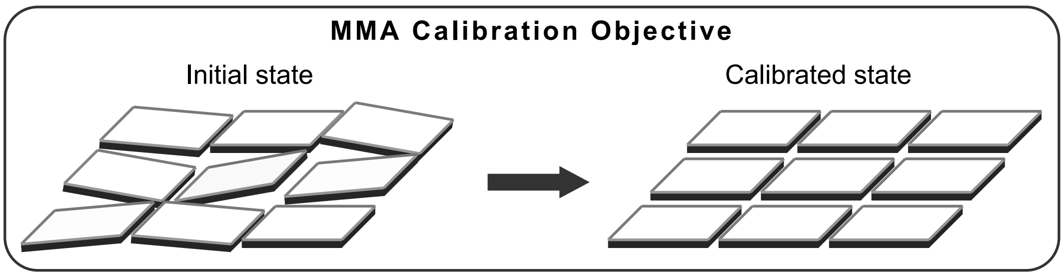

Figure 6: Illustration of MMA calibration objective. Deflection variations should be corrected to enable precise mirror deflection states at nanometer scale.

Luberek et. al. presented in [10] a practical method to perform the calibration of the projected illumination patterns by improving a certain grayscale uniformity that finally reduces the CD error contribution of the MMA. Our study differs from Luberek's one in that we do not measure the optical device response directly, we measure the mechanical mirror deflection. Hence, indirectly, the grayscale uniformity of the shadow mask will be improved and the error contribution reduced. Main benefit of our approach is the utilization for several application wavelengths.

Goal of the present work is the determination of the individual mirror voltage-deflection-curves. This task comprises the handling of certain amount of data in manageable time (64k micromirrors), which gives a clear indication for an automation task. While earlier measurement systems easily may have reached that goal with a standard white light interferometer (WLI) [14], the present study also incorporated a distinct WLI system with time resolved capabilities to account for special transient effects in the deflection characteristics [15]. A commercial profilometric measurement system was identified as very suitable to perform the parallel surface measurements of a large number of micromirrors with z-accuracy in the sub-nanometer scale and with the desired time resolution. Remote control of the profilometric measurement system provides the opportunity to run the profilometer setup and calculations automatically controlled by an external computer. By means of multiple driving voltage measurements the electro-mechanical response curve for every MEMS actuator will be achieved (Figure 7). This measured set of curves will be finally used for the accurate micromirror positioning of the MMA.

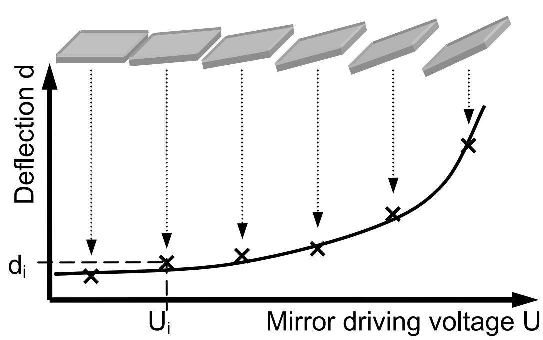

Figure 7: Set of measurement points at various mirror driving voltages U_i characterizing the voltage-deflection-curve.

4. SYSTEM IMPLEMENTATION

The calibration procedure has been studied within a table top setup, where a single computer allows the fully automated operation of all components involved. The system layout is sketched in Figure 8.

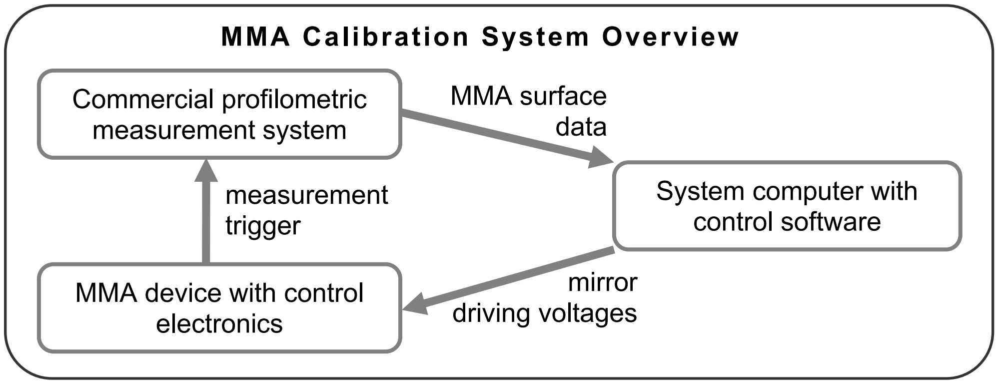

Figure 8: Overview of the calibration setup. The control computer generates mirror driving voltages which are transferred to the MMA electronics. When the mirrors are deflected a trigger signal activates the profilometric measurement. The final profile data return to the control software for analysis.

The assembly's master unit is the system computer with its control software, which

- arranges the interaction between all system components,
- receives and analyzes the measured MMA surface data,
- provides the mirror driving voltages for the pattern and
- executes relevant calculations.

Challenge in the system concept is the appropriate handling of all micromirror data as well as the dynamic mirror control at a frame rate of 1 kHz, which has to be linked to the profilometric measurement system.

The next two paragraphs illustrate the system operation principle in more detail.

4.1 Determination of mirror deflections

The profile of up to 6 000 micromirrors is measured during a single data acquisition cycle. Taking into account the continuous surface data provided by the profilometer, a special routine is necessary to extract the relevant mirror deflection data automatically [16]. A sectioning routine, based on pattern convolution, is initially applied to divide the continuous profile into areas representing the single actuators (Figure 9). Areas of posts in the mirror plate's middle and slits between the mirrors are removed to isolate valid data points.

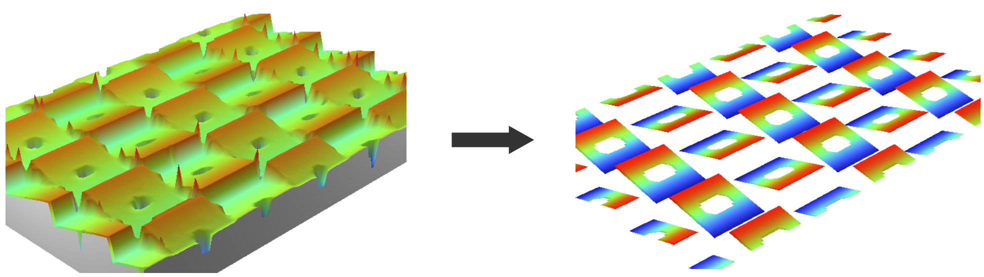

Figure 9: Illustration of raw profile segmentation to extract the mirror data.

In a second step, the analysis of all separated mirror regions is carried out with a regression analysis for all individual mirror planes. Using the tilt data results, the mirror deflection can be derived directly. The complete data extraction procedure takes few seconds for all 6 000 actuators and therefore meets the goal of reasonable time consumption.

4.2 Additional steps for calibration

The measurement routine needs to be repeated for various mirror driving voltages in order to obtain a sufficiently complete "calibration" data set. The driving voltages are selected in a way that the determined deflections represent a predefined range starting with zero up to maximum deflection. Typically less than 10 sampling voltages are required to enable a precise regression of the deflection characteristics.

Subsequently, an appropriate fit function is used to transfer the measured voltage-deflection-response into a small set of coefficients for every individual mirror. We tested standard analytical functions as well as tailored series expansion with principal functions. For all cases, few parameters per micromirror describe the complete deflection characteristics. Main observation of the array properties are generally the variation in the curve slope and the individual deflection-offset terms of the mirrors.

To proceed with the calibration, a stepping algorithm is used to raster the complete MMA area with the profilometer measurement field (comprising 6 000 micromirrors). By means of field stitching, all 64k mirrors are automatically measured and completely characterized within a time of half an hour. Outcome of the procedure is a data file comprising the coefficients that may predict the individual tilt of each single mirror within the array.

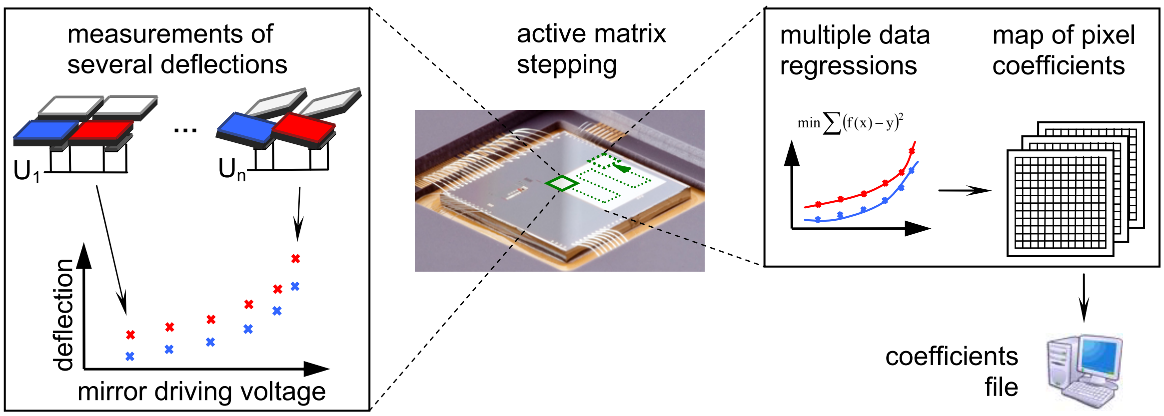

Figure 10: Simplified calibration routine work flow.

5. RESULTS AND DISCUSSION

Goal of the calibration activities has been the precise deflection of all 64k micromirrors during the user defined operation states. This section discusses the calibration results from two perspectives. Firstly, the calibration accuracy is directly tested within the relevant deflection range by means of a standard profilometric system to estimate the status, reached with the current work. This is accompanied with the comparison of a simple MMA deflection pattern with and without calibration to elucidate the gain of performance that can be reached by the basic procedure. Secondly, the optical quality of MMA illumination patterns is considered with and without calibration to also approach the application relevant optical effects.

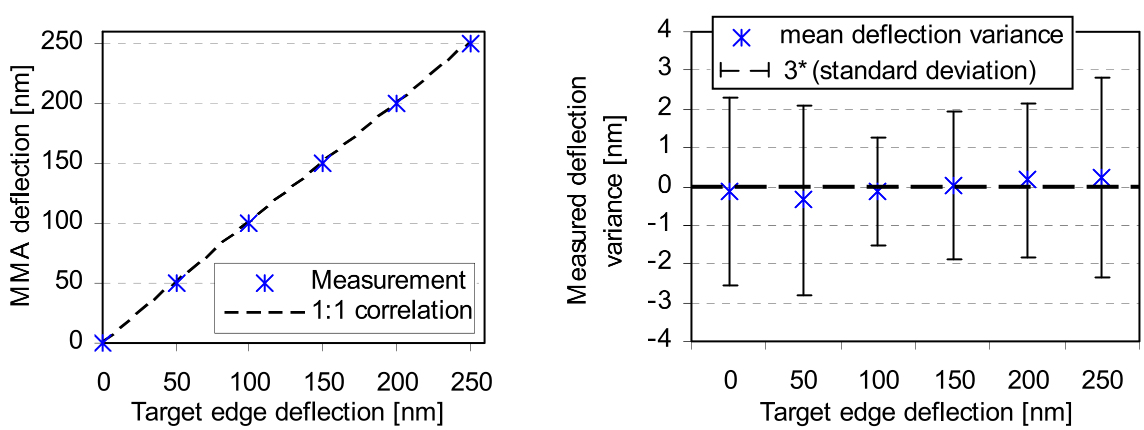

Figure 11: Calibration accuracy for a sequence of deflection states. The data plots depict the difference between target and measured deflection, based on ca. 6 000 actuators. The right graph illustrates magnified deviations to resolve the remaining small discrepancies. The deflection states cross the whole application range (DUV – NIR).

Figure 11 illustrates the very straight correlation of the real MMA deflection with the expectation value. The remaining discrepancies are resolved with the right figure's zoomed plot, which shows that i) the mean target deflection is well below 1 nm accuracy and ii) a spread of less than 3 nm is reached in the entire deflection range (data are calculated from 6 000 single mirrors of one profile measurement field). Obviously, the MMA control between 0 … 250 nm deflection can be achieved within the anticipated accuracy of λ/100 by means of MMA calibration.

Figure 12 shows the direct comparison of calibrated and non-calibrated mirrors at 250 nm target deflection for the complete MMA area (necessary for NIR operation at 1000 nm). The different colors indicate mirror deflections in the array. One can observe very clearly the strong increase of deflection homogeneity between the two states. Initially, "global" variations of the mirror deflections are present (the whole array is controlled with one global addressing voltage; several reasons for a deflection spread apply). The transition to the calibrated state removes that variation completely due to the proper application of individual address voltages for each single mirror, which is further underlined by the histogram viewgraph. The total spread of deflection decreases by more than a factor of 10, indicating the very high suitability of the calibration routine to compensate small fluctuations and also larger systematic artifacts related to the CMOS electronics and/or MEMS technological variations.

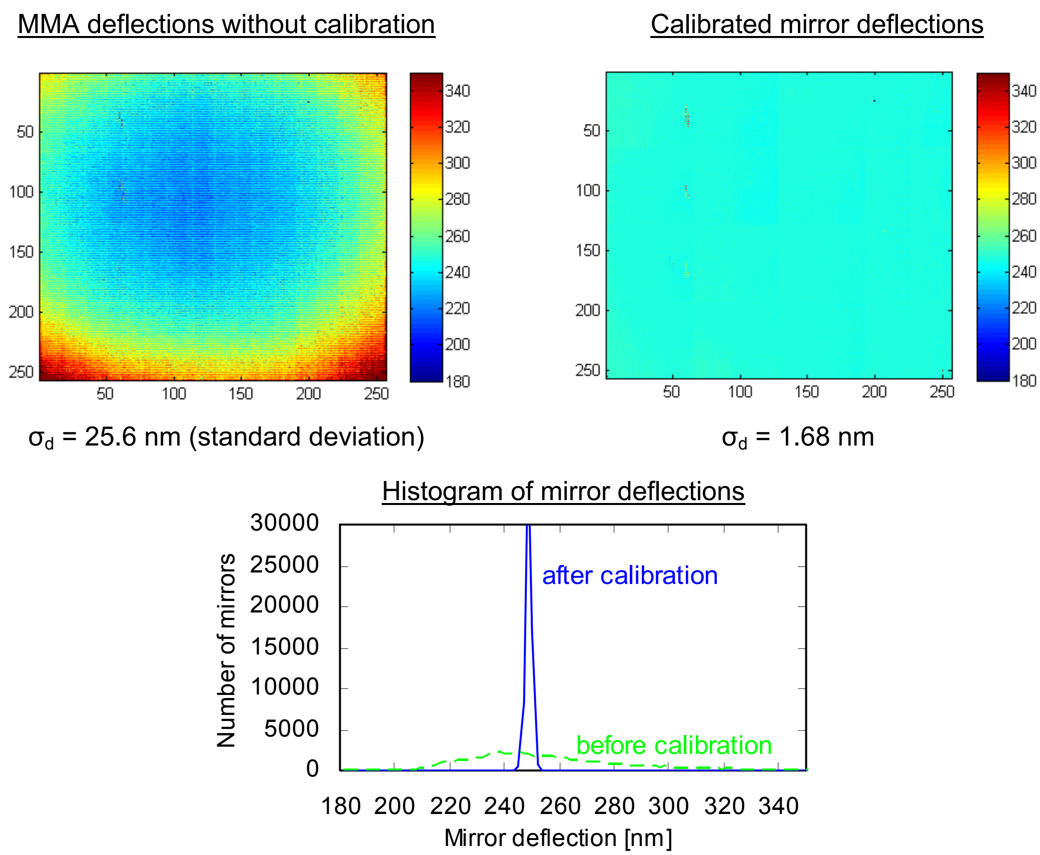

Figure 12: Comparison of measured MMA deflections at a target deflection of 250 nm. Upper left image shows non-calibrated deflections resulting from the same address-voltage applied to all mirrors. The right image plots the calibrated mapping of mirror deflections. The histogram illustrates the extreme gain of accuracy (one order of magnitude) by the calibration process.

We studied the optical consequences of calibration effects with a previously developed laser characterization system for diffractive MMAs. The setup comprises sources of the relevant DUV/VIS/NIR spectral range, beam homogenization capabilities with divergence control, an adjustable Fourier optics and a time resolved detection system to record MMA modulated illumination patterns. Full component control and synchronization allows device research and illumination pattern characterization close to application conditions. More setup details are described in [7].

Two advantages of MMA calibration can be seen clearly in Figure 13 a) which shows a recorded test pattern generated by the mentioned setup. Firstly, significantly improved illumination homogeneity of bright structures is reached compared to the non-calibrated areas (Figure 13 b). Intensity variations are clearly apparent in the zoomed area, brighter and darker stripes generated by single mirror columns in the array resulting from a special sample effect. In comparison the lower image part was created by calibrated micromirrors with individual control. Homogeneity enhancement and less intensity scatter is an evident result. Qualitatively, homogeneity in the range of 1 % can be achieved with the correction of local deflection artifacts. Secondly, the uniformity of areas with lowest possible intensity ("black") is strongly increased, which enables high contrast imaging capabilities. Figure 13 c) displays cross sections in calibrated/non-calibrated regions of a "black" pattern. Although image (a) displays no differences by eye inspection, the cross sections of image (c) easily elucidates the difference. The spatial intensity variation of the non-calibrated area is apparent, and similar to the profilometric measurement in Figure 12. MMA calibration compensates this device characteristic successfully. Last but not least - the flower's image indicates the capability to generate high quality, real time grayscale images within a calibrated MMA area.

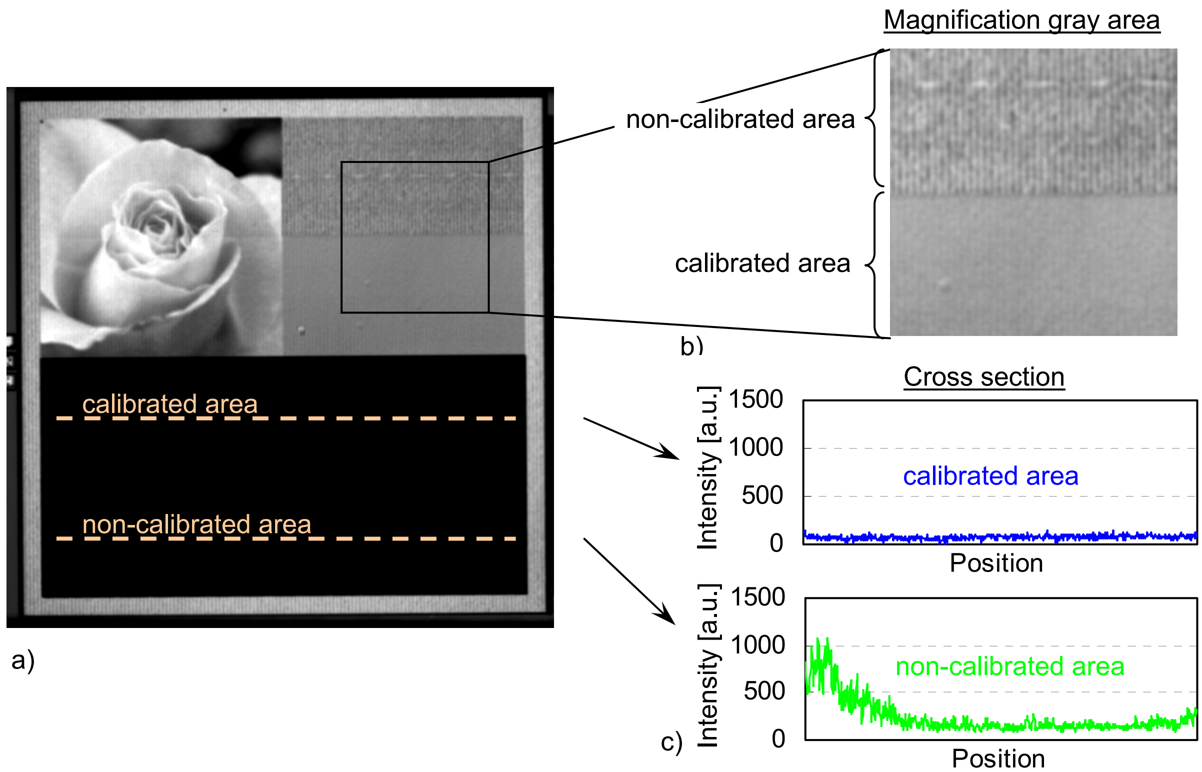

Figure 13: Recorded sample pattern to illustrate the calibration effect (a). The image part of the rose demonstrates the MMA's ability to generate gray patterns. Increasing uniformity with calibrated actuators is shown in b) by the help of a gray pattern. The lower part shows a black pattern where the upper part is calibrated, the lower half is not. Their cross sections (c) depict compensation of device properties and decreasing of intensity level.

The contrast properties of micromirror arrays have been the central interest for the current work. Looking into the experiments performed, in fact all measurements confirm a strong increase of contrast after calibration. Typically an improvement by a factor of 2 or even higher has been recorded with this operation mode. Absolute contrast values of standard technology samples range above 500, distinctive good spots even could still not be measured until now since they reach the upper limit of the measurement system (contrast limit of 800…1 000). The relative improvement certainly depends on the initial "non-calibrated" state, but the final state now is no more constrained by the spread of mirror deflections. The maximum MMA contrast becomes a function primarily of the single mirror deformation [8], which is guaranteed from the new MMA technology to locate in a very comfortable range well below λ/100 [6].

The contrast increases with illumination wavelength, independently, whether calibration is present or not. This characteristic behavior has been recorded (Figure 14). The spectral contrast curve, measured for a special sample with a selected high mirror roughness, fits well into parts of the dynamic range of the optical measurement system. It displays the typical increase of MMA contrast with longer wavelengths for non-calibrated and also calibrated MMAs (except the saturated data at resolution limits). Standard samples with low mirror roughness already start with higher contrast values at short wavelength that early surpass the current resolution limit of the analysis setup.

Measurements finally indicate that the initial goal of high MMA contrast operation indeed is met with the calibrated MMA option and the current MEMS technology. It concludes successfully the project work for the MMA technology exploration and paves the way for multispectral applications of diffractive micromirror arrays.

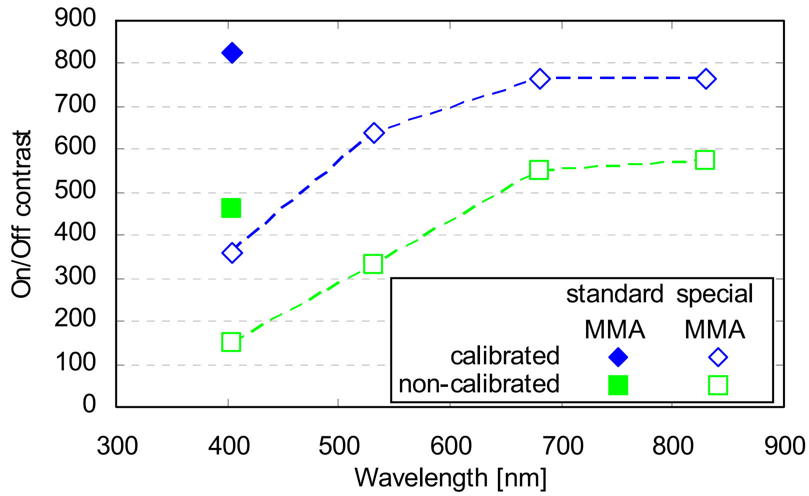

Figure 14: Measured contrast values with/without using MMA calibration data in a broad spectral range. The contrast increases with illumination wavelength and with calibration. (Note: the current optical measurement system has a noise-limited contrast detection nearby 800-1 000, thus a “special MMA” with limited contrast potential was chosen to enable a broad spectral measurement).

6. SUMMARY AND CONCLUSION

We studied a fully automated calibration routine for diffractive micromirror arrays based on a standard profilometric measurement system. The mirror deflection of every actuator element has been characterized in order to enable an accurate mirror control. Each mirror deflection now can be adjusted well in the $\lambda/100$ accuracy range. Thanks to that high precision, the calibration procedure strongly improves illumination pattern quality. Uniformity enhancement and less intensity scatter is an evident result. Contrast data up to 800 demonstrate great progress in device development and control of MMA deflection. The devices fulfill essential optical requirements for new microscopy application with precise illumination modulation in a broad spectral range. This way, the work performed holds good news for enhanced micro-imaging applications with a new device option to increase system performance.

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REFERENCES

[1] Sampsell, J., "An Overview of the Performance Envelope of Digital Micromirror Device Based Projection Display Systems", SID Int. Symp. Digest Tech. Papers, 669-672 (1994).

[2] Gehner, A., Wildenhain, M., Neumann, H., Knobbe, J. and Komenda, O., "MEMS analog light processing – an enabling technology for adaptive optical phase control", Proc. SPIE 6113, 1-15 (2006).

[3] Sandström, T., Askebjer, P., Sallander, J., Zerne, R. and Karawajczyk, A., "Pattern Generation with SLM Imaging", Proc. SPIE 4562, 38-44 (2002).

[4] MEMI – Micromirror Enhanced Micro-Imaging, www.memi-fp7.org

[5] Kielhorn, M., Cox, S., Ipp, E. and Heitzmann, R., "Spatio-angular Microscopy", Proc. SSI (2011).

[6] Schmidt, J.-U., Bring, M., Heber, J., Friedrichs, M., Rudloff, D., Rößler, J., Berndt, D., Neumann, H., Kluge, W., Eckert, M., List, M., Müller, M. and Wagner, M., "Technology development of diffractive micromirror arrays for the deep ultraviolet to the near infrared spectral range", Proc. SPIE 7716, 77162L (2010).

[7] Berndt, D., Heber, J., Sinning, S., Kunze, D., Knobbe, J., Schmidt, J.-U., Bring, M., Rudloff, D., Friedrichs, M., Rössler, J., Eckert, M., Kluge, W., Neumann, H., Wagner, M. and Lakner, H., "Multispectral characterization of diffractive micromirror arrays", Proc. SPIE 7718, 77180Q (2010).

[8] Heber, J., Kunze, D., Dürr, P., Rudloff, D., Wagner, M., Björnängen, P., Luberek, J., Berzinsh, U., Sandström, T. and Karlin, T., "Contrast properties of spatial light modulators for microlithography", Proc. SPIE 6730, 673035 (2007).

[9] Gaskill, J.D., [Linear System, Fourier Transforms, and Optics], Wiley, New York (1978).

[10] Luberek, J., Carroll, A., Sandström, T. and Karawajczyk, A., "Controlling CD Variations in a Massively Parallel Pattern Generator", Proc. SPIE 4691, 671-678 (2002).

[11] Corrigan, R., Amm, D., Alioshin, P., Staker, B., LeHoty, D., Gross, K. and Lang, B., "Calibration of a Scanned Linear Grating Light Valve Projection System", SID Int. Symp. Digest Tech. Papers, 220-223 (1999).

[12] Latypov, A. and Poultney, S., "System and method for calibrating a spatial light modulator array using shearing interferometry", Patent No. US 6,847,461 (2005).

[13] Berndt, D., "Software für die zeitoptimierte Kalibrierung von Mikrokippspiegeln", Master Thesis (in German), TU Dresden (2007).

[14] Dürr, P., Gehner, A. and Dauderstädt, U., "Micromirror Spatial Light Modulator", Proc. Optical MEMS, 60-65 (1999).

[15] Grigg, D., Felkel, E., Roth, J., Colonna de Lega, X., Deck, L. and de Groot, P., "Static and dynamic characterization of MEMS and MOEMS devices using optical interference microscopy", Proc. SPIE 5455, 429-435 (2004).

[16] Novak, E., Krell, M. B. and Brown, T., "Template-based software for accurate MEMS characterization", Proc. SPIE 4980, 75-80 (2003).