Application specific Micro Scanning Mirrors

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Abstract

Optical scanning is a common technique with numerous applications in data caputre, projection, 3d measurement etc. A single crystal silicon (SCS) mirror technology based on BSOI (Bonded Silicon on Insulator) wafers is presented to fabricate 1D and 2D scanning mirrors. The mirrors are resonantly driven by means of in-plane comb electrode configuration. Comperad to conventional polygon or gavanometer scanning systems use of Micro Scanning Mirror Technology offers several advantages like high scan frequencies, extreme miniaturization, excellent reliability, no wearing or wobbling and the potential for low cost manufacturing at high volumes. However, technology development for application specific requirements is cost and time consuming. To reduce the efforts to realize a customized microscanner IPMS now introduce the new technological platform VarioS enabling first application specific demonstrator samples at reduced efforts in time and cost. The potential of the MEMS mirrors is shown by selected applications: e.g. an ultra compact projector and a micro laser camera for endoscopes.

Keywords: MOEMS, micro scanning mirror, laser display, scanning beam imaging, 3D laser camera

1 Introduction

Optical scanning is a well known and widely spread technique to collect data [1], to measure 3D topologies, to project images or to scan the lights' spectral components across a single detector [2]. Use of Micro Scanning Mirror Technology offers several advantages like high frequency scanning and extreme miniaturization of scanning systems. At Fraunhofer IPMS a qualified micro scanning mirror technology with high flexibility and several options including diffraction gratings [2], integrated position sensors [3] and highly reflective coatings [4] was developed. The process, offered by MEMS Technologies Dresden, is based on the use of BSOI wafers with a 75 µm thick SOI layer. The mechanical elements as well as the driving comb are generated by means of a DRIE etch. In addition to several process options the design space was increased by special design features like e. g. distributed springs to keep mirror flatness extremely high even at high frequencies. However, cost for technology development in particular for application specific requirements are high and often the development time is too long. In this paper Fraunhofer IPMS presents now the VarioS microscanner construction kit, which allows customers to receive customized MEMS scanner demonstrators within a few weeks time at resonable lower costs. This gives a significant step in making high-tech scanner technology easily accessible to product developers. In chapter 3 this paper gives a brief overview on the principle of operation and properties of SCS mirrors developed at Fraunhofer IPMS. Chapter 4 describes the basic fabrication technology using Bonded Silicon on Insulator (BSOI) wafers and chapter 5 presents the cost efficient platform VarioS. Finally, in chapter 6 the potential of the scanning micro mirrors is presented by selected applications: e.g. an ultra compact VGA projector, a SVGA micro laser camera for endoscope applications, a scanning photon microscope, a large aperture MEMS scanner module developed for 3D laser disctance measurement.

2 Basic architecture

Basic element of the scanning micro mirrors developed at Fraunhofer IPMS is a mirror plate suspended by two springs etched from a single crystalline silicon layer as illustrated in the upper part of Fig. 1.

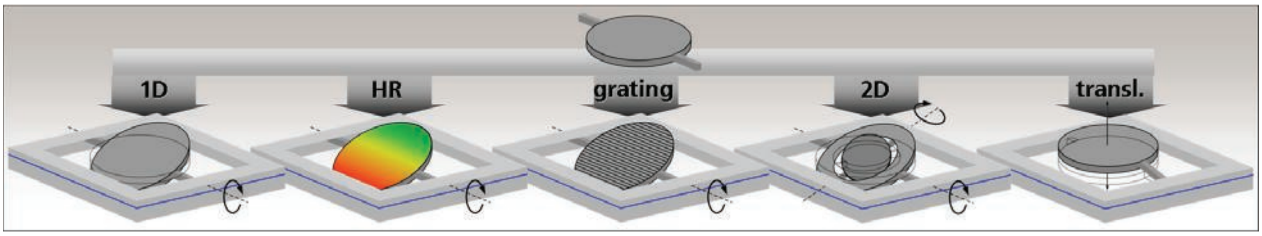

Fig. 1. Basic architecture and derived variants. From left to right: 1D rotational, highly reflective coating, scanning grating, 2D rotational, translation mirror.

From that, several variants are derived. With torsional suspension 1D scanners with or w/o high reflective coatings e.g. for barcode scanning or laser treadment [4] can be realized. By patterning of the mirror plate scanning gratings for spectroscopy can be fabricated [2]. A gimbal mount of the mirror plate allows for 2D deflection e. g. used for projection displays. By supporting the oscillating mirror plate with bending springs or using a phantograph suspension a translatory mirror is realized for optical path modulation [7] e.g. for confocal microscopy or FT-spectrometry. Finally, combinations of all the shown variants are possible.

3 Principle of operation

The devices are excited resonantly by electrostatic forces/torques using a in plane configuration of the driving comb electrodes. As the driving force/torque given by the pulsed voltage applied to the combs depends on the frequency, the oscillator is a parametric oscillator. It yields oscillation amplitudes in the range of several degrees. Optimum excitation is achieved when the driving voltage is switched off exactly when the mirror passes the rest point and is switched on at the maximum angle of deflection. A typical response curve is shown in Figure 2c for the case of a rotational mirror with torsional beam springs.

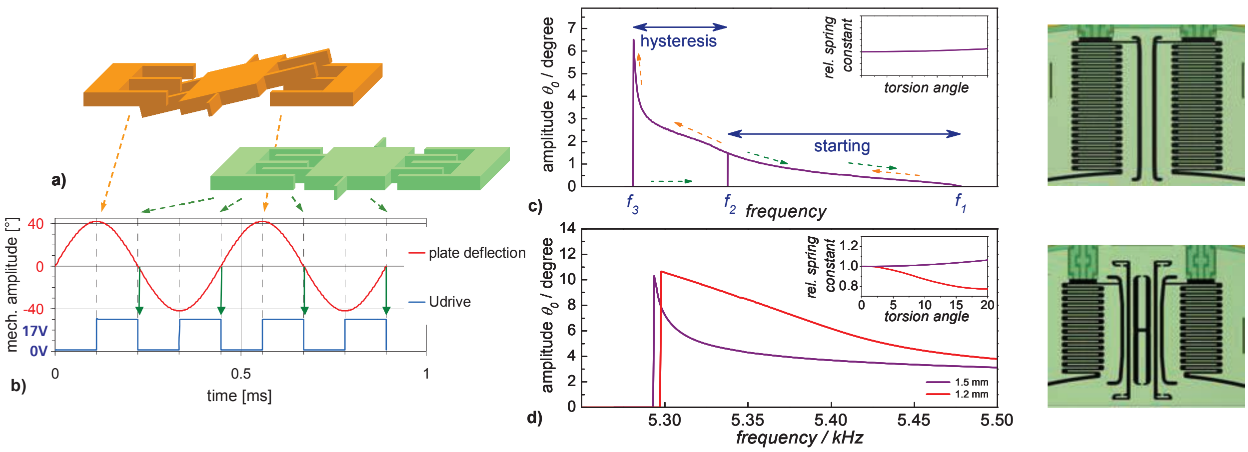

Fig. 2. Left: resonant driving principle (a & b); Right: Typical response curve of a rotational mirror (c). The torsion spring (micrograph on the right) is slightly progressive. Fig. 2d) Comparison of the response curves of a scanner with progressive (violet) and degressive (red) spring. Micrograph of the degressive spring. Multiple springs, parallel to each other are deployed.

Depending on the sweep direction of the excitation frequency different parts of the curve are valid. Start of the oscillation is limited to the frequency range from f2 to f1. Only if the frequency is swept downwards the maximum oscillation amplitude is reached. Near to the maximum the slope of the curve is steep and the oscillation is not very stable finally breaking down at frequencies smaller than f3. Therefore, safe operation requires staying a few Hz below maximum. This is typical for a spring where the spring constant is approximately independent from the deflection angle, (see inset of Fig. 2c). With a special design of the springs a degressive slope can be obtained as shown in the inset of Figure 2d. The net effect is a much broader response curve. This allows a stable operation without sacrificing a larger amount of the maximum possible scan angle. Another method for stable operation is to read-out the cross over of the oscillation and to synchronize the falling edge of the driving pulse to the cross-over (see e. g. [8] [14]).

4 Fabrication process

In the following a description of the basic fabrication process is given. Typically, a 75 µm thick highly doped SOI-layer with a 1 µm thick buried oxide (BOX) layer is used as base material (Fig. 3a). Vertical trenches with a width of app. 1 µm are dry etched into the SOI-layer (Fig. 3b). Thermal oxidation and refilling with polysilicon (Fig. 3c) allows for electrical isolation of neighboring areas. The next steps comprise silicon dioxide and aluminum layer deposition and patterning, providing electrical wiring and bondpads (Fig. 3d). A layer of aluminum serves as reflective coating (Fig. 3e). In the next step, the substrate underneath the mechanical elements is removed with TMAH-etch. Next, the BOX-layer is removed in a buffered oxide etch solution. Finally, vertical trenches with a typical width of 5 µm are etched into the SOI layer which define the mechanical structures and the electrodes (Fig. 3f).

Main features of the process are a) a well defined thickness of the mechanical elements (springs, mirror plate, etc.) by the SOI-layer, b) vertical sidewalls of the trenches by a DRIE-process defining e. g. springs and electrode combs, c) open and filled insulation trenches where latter ones can also be used on movable elements, d) the use of the single crystal silicon layer as electrical conductor and e) complete removal of the substrate underneath the mechanical elements allowing very large deflections.

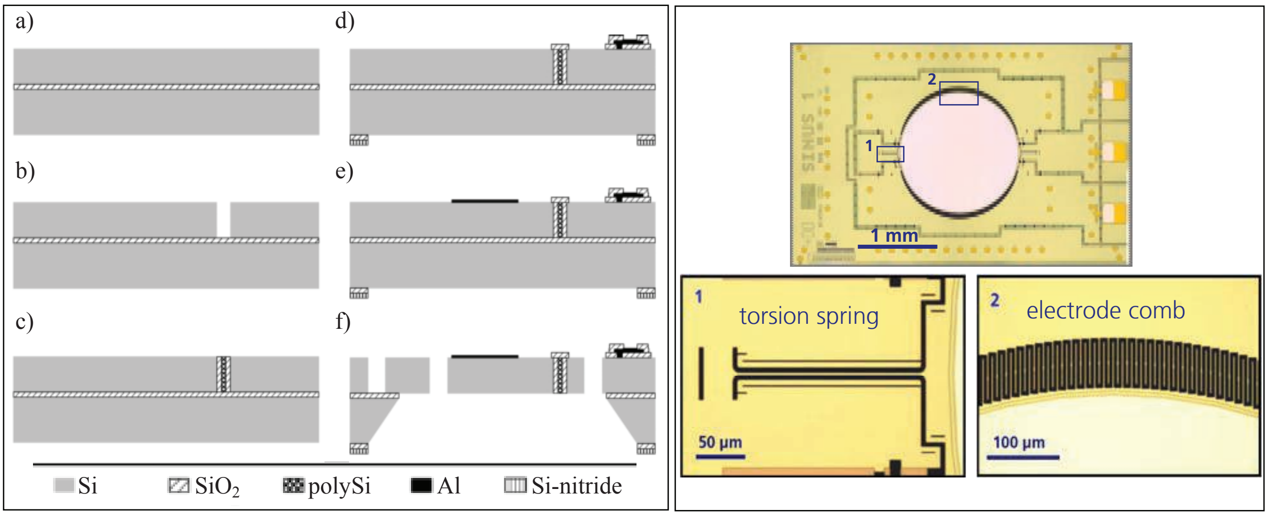

Fig. 3. Left: Basic fabrication process. Right: Micrograph of a 1D scanner chip with a mirror diameter of 1.5 mm. Chip size is 4.3 x 2.9 mm². Bottom right: Details of the torsion spring with a width of 1.8 µm and the electrode comb with an electrode gap of 5 µm.
The right hand side of Figure 3 shows a 1D-scanner chip with a resonance frequency of 250 Hz. The optical scan range is up to 100°. By means of process options the functionality of the scanners can be expanded. The options include integrated piezo resistive sensors [3] for position detection, highly reflective coatings [4] and fabrication of gratings [2].

5 VarioS – a microscanner construction set

Using its basic scanner technology IPMS developed the modular platform *VarioS* - consisting of (i) a webinterface at www.micro-mirrors.com for online configuration of individual scanner devices and (ii) a modular scanner fabrication using prefabricated wafers enabling customer specific microscanners for demonstration at short lead time at low costs. The Scanner-Configurator [6] may be used to easily configure a micro scanner-demonstrator for testing specific applications and receive demonstrator devices at low cost and within a relatively short time (6 to 9 weeks). Lead time depends on, whether a fitting design is (i) in stock (3 weeks), (ii) modular (6 weeks) or (iii) semicustomized fabrication (9 weeks). Demonstrators can be freely configured within our design space varying basic micromirror properties (e.g. mirror diameter, scan frequency etc.) to meet individual customer requirements. Customers may use the webinterface to verify the feasibility of their demand and request a quotation for their specific design.

For VarioS the fabrication of a customiced scanner design is performed at the facilities of Fraunhofer IPMS using preprocessed wafers. This allows for a fast response time for the final design parameters requested by the customers. Currently IPMS can offer 1D devices and will soon be able to extend this service to 2D devices. The mirror plate and mechanical structures consist of single crystalline silicon (c-Si) with an aluminum mirror coating yielding approx. 86 % reflectivity in the visible range. The static deformation of the mirror plate usually shows a radius of curvature > 5 m. The scan frequencies (resonant driving principle) can be set between 100 Hz - 50 kHz depending on the mirror size and the mirror diameters which can be chosen from 0.5 mm – 3 mm. The devices are delivered in a DIL14 ceramic housing with broadband ARC glass cover. Figure 4 a-b show examples of the modular design space for preprocessed wafers carrying a reflective coating of a predefined size (standardized values of mirror diameter are 0.5, 1, 1.5, 2, 3 mm). Figure 4 (rigth) reveals the final design of a 1D scanning device. The VarioS 1D-scanners can be combined with the modular system platform LDC (laser deflection cube) of IPMS enabling a complete miniaturized scanning module including driving electronics, packaging etc. [14]

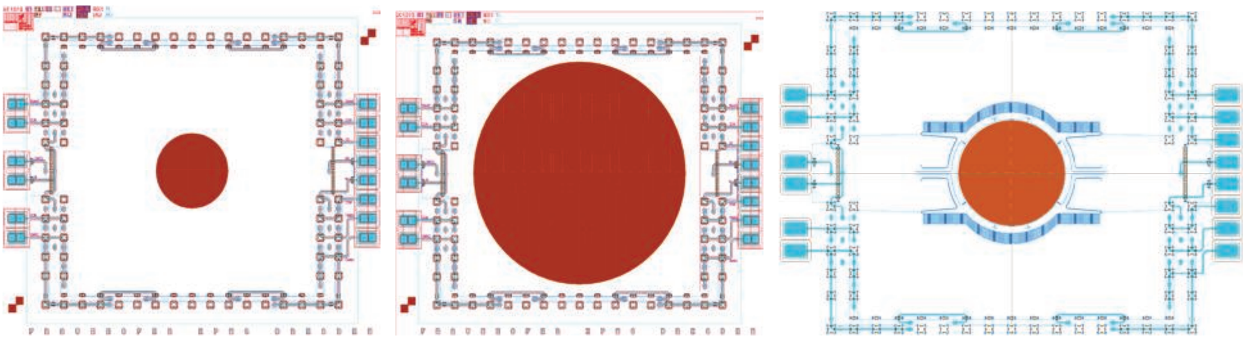

Fig. 4. Modular IPMS platform VarioS for customized scanner demonstartor samples using prefabricated BSOI wafers; MEMS layout of prefabricated scanner with 1 mm mirror (left), 3 mm mirror (middle) and final MEMS layout of a 1D-micro scanning mirror

6 Selected applications

6.1 Ultra compact projector

Based on a 2D micro scanning mirror (see Figure 5) a highly compact projector was realized. The bi-sinusoidal oscillation of the resonantly driven scanner results in a Lissajous-pattern. This special trajectory has to be taken into account for the laser intensity modulation. The principle set-up of the projector with its most important components is illustrated in Figure 5 for a full color display. The video data to be displayed are transferred to FPGA electronics and intermediately stored in a RAM. The data processing re-arranges the pixels according to the Lissajous-trajectory in real time. Additionally, grey levels are adjusted to the bi-sinusoidal oscillation which e. g. results in a slower scan at the edges of the image. The digital data are then transformed into analog voltages taking into account the characteristics of the laser diodes as well as synchronized to the phases of the 2D mirror oscillation.

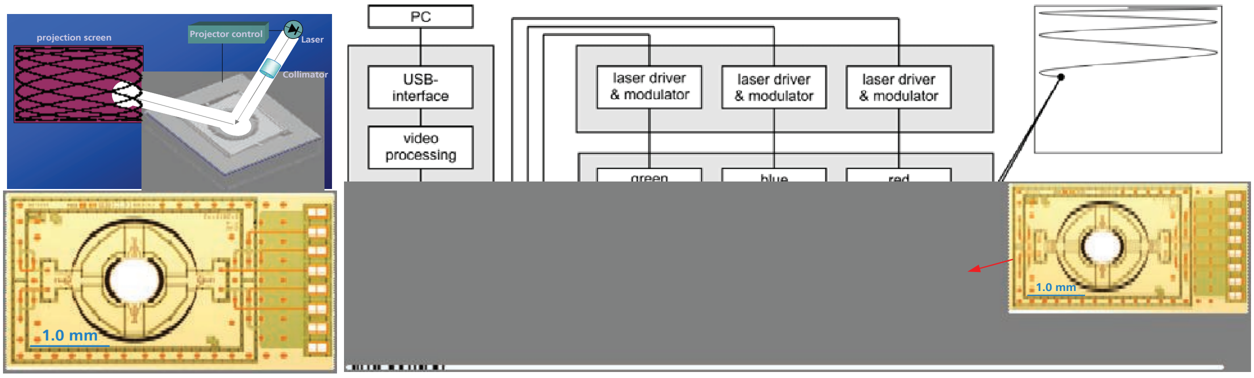

Fig. 5. Left: Principle of Lissajous-projector; Micrograph of the 2D scanner chip. Right:. System architecture of a full color display

The set-up of a monochrome VGA projection module is shown in Figure 6. The module allows for projection of images and videos with a frame rate of 50 Hz and a grey value depth of 8 bit. Internally a 12 bit grey value scheme is used to correct for the varying scan speed due to the Lissajous-trajectory. A detailed description of the projectors electronics is published elsewhere [9]. The test image shows that despite the Lissajous-pattern text and figures with arbitrary shape can be projected. Using three laser diodes (red green blue; RGB) a full color image can be displayed using a single 2D scanning mirror. For that, the electronics supports three data/modulation channels [9]. Due to the fact that highly miniaturized green laser diodes of suitable modulation bandwidth were not available at the time of projector realization the dimensions of the shown RGB-projector are considerably larger than that of the monochrome red projector. Instrumentation and a projected image are shown in the right part of Figure 6.

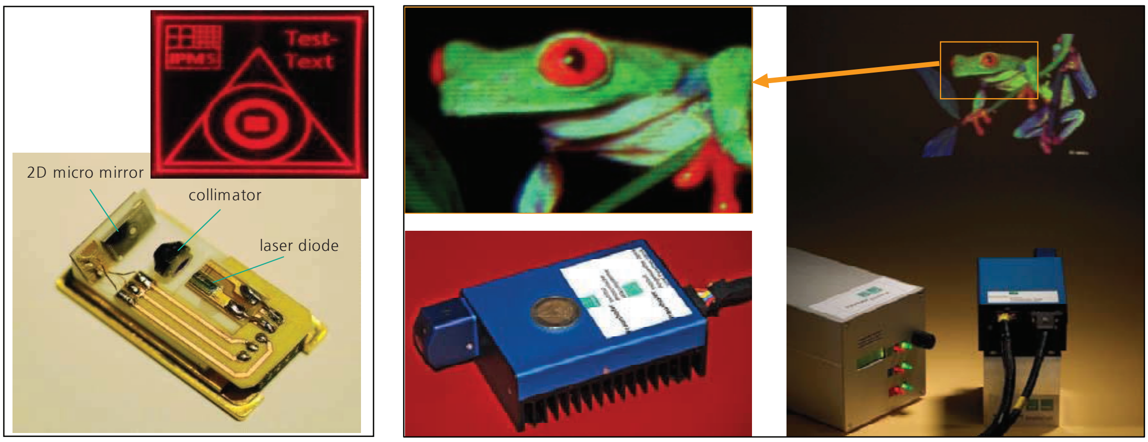

Fig. 6. Left: Ultra compact monochrome projection module of 17 x 7 x 5 mm³ size. The electronics realized as FPGA (not shown). Right: RGB-projector with projected image. The size is 10 x 7 x 4 cm³. Both modules were built in cooperation with Fraunhofer IOF.

6.2 Micro Laser Camera

The system architecture of the scanned beam imaging system [10], [11] making use of a customized resonant 2D-scanning mirror is illustrated in Figure 7. Three lasers (RGB) are combined with dichroitic filters and focused onto a single mode glass fiber which guides the light to the 2D scanning mirror. The mirror scans the subject along a Lissajous-trajectory. The diffusely reflected light from the subject is collected by several multimode fibers. Three dichroitic mirrors direct the respective RGB components on three thermoelectrically cooled Avalanche photodiodes. Additionally, a detector for fluorescence signals can be implemented (not shown in the Figure). The signal at the respective detector is amplified and digitized with a rate of 50 MHz and 12 bit resolution. From the time dependent signal and the corresponding deflection angle of the 2D scanning mirror the image is reconstructed in real time. The mirror diameter is 0.5 mm. The optical scan range is 112° x 84° at a frequency of 1 kHz for the slow axis and 16 kHz for the fast axis. With that, SVGA resolution at a repetition rate of 30 Hz is achieved. Figure 7a shows a photograph of the 8 mm diameter endoscope tip including the glass fibers. A picture taken through the glass dome shows the assembled scanning mirror. The mirror contains a 50 µm hole for illumination from the backside. A full color sample image with SVGA resolution is shown in Figure 7c.

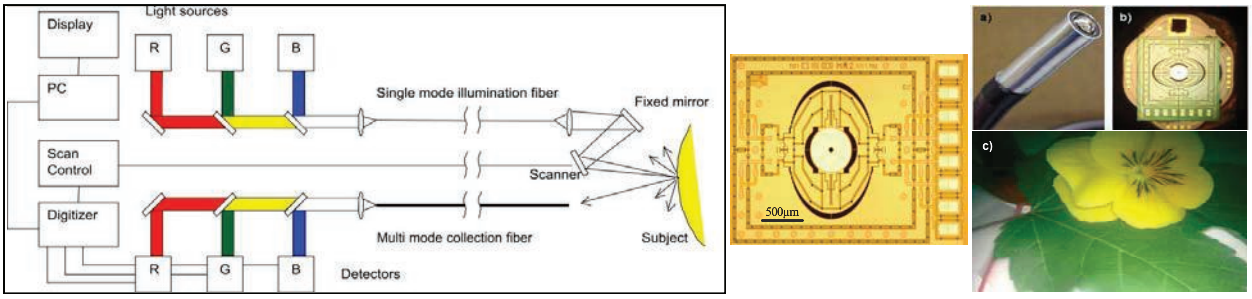

Fig. 7. Left: System architecture of the micro laser camera, Middle: Deployed 2D scanning mirror, Rigth: a) Endoscope tip of 8 mm diameter. b) Photo through the glass dome. c) Sample image with SVGA resolution. (courtesy of Microvision).

6.3 Scanning Photon Microscope

Above described approach to scan an image was applied to microscopy. The optical set-up makes use of a telecentric objective lens as shown in Figure 8. The laser beam is scanned two dimensionally across the sample. The back-reflected light is directed to the photo detector via a beam splitter. Using an aperture stop darkfield operation is enabled, too. The resolution of the current system is 10 µm. A sample image is shown in the left part of Figure 8. Details of the system are given in [5].

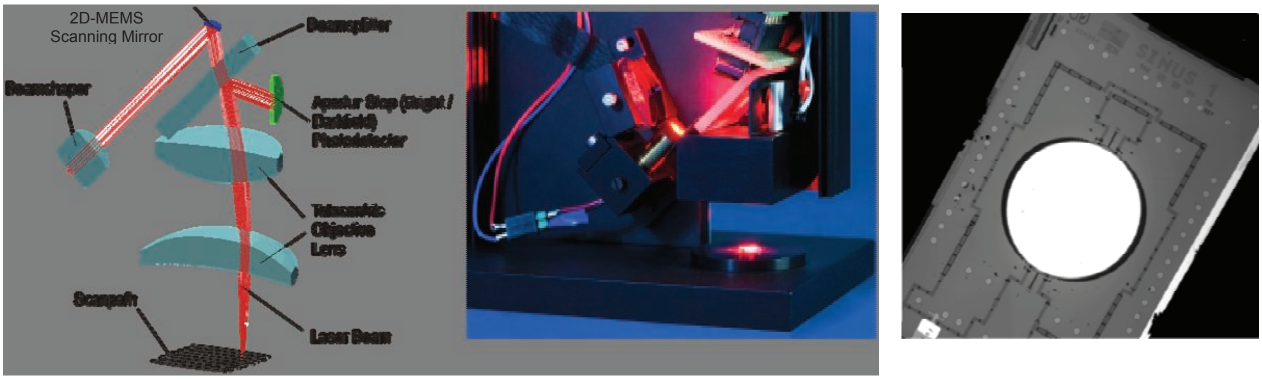

Fig. 8: Left: Optical path in the Scanning Photon Microscope. Middle: Photo of the actual optical set-up. Right: Image of a 1D scanner chip taken by the microscope.

6.4 Large aperture MEMS scanner module for 3D distance measurement

Based on IPMS scanner technology a large aperture 1D-MEMS scanner module have been developed for a 3D laser scanning TOF camera with phaseshift-distantance measurement used e.g. for mobile 3D documentation in architecture etc. [12]. The scanner module comprises of two separate scanning channels: (i) a single scanning mirror of the collimated transmitted beam oscillates parallel to (ii) a scanning mirror array of the receiver optics (see fig. 9). The receiver optics use a synchronized 2 x 7 array of 14 identical scanner elements, each with 2.51 x 9.51 mm² per single mirror element, resulting in a total aperture of 334 mm² and filling factor of 80 % [13]. The mirrors' oscillations are synchronized to the sending master mirror in frequency and phase by driving control using hybrid integrated optical sensors for position feedback of each scanner element. The MEMS scanner array itself satisfies at the same time the demand of a comparatively large optically active area of 334 mm², while keeping the resonance frequency of 250 Hz at a value that matches well to current ToF laser distance measurement systems with point measurement rates of typical 250…1000 kHz. Thus, the optical scan range of 60° degrees is split into 500 - 2000 intervals. The new concept of using an array of synchronized identical MEMS mirror elements permits large reception apertures for LIDAR systems while preserving the outstanding reliability, high scanning speed (equal to a conventional rotational polygon scanner of 30000 turns/min) without any wearing of beerings, compact size and small system weight that can be expected from MEMS.

The concept of MEMS based LIDAR system can realize also high accuracy of the distance measurement similar to state of the art TOF-LIDAR scanners enabling a new generation of miniaturized, robust, portable and potentially cost efficient LIDAR systems due to the MEMS technology.

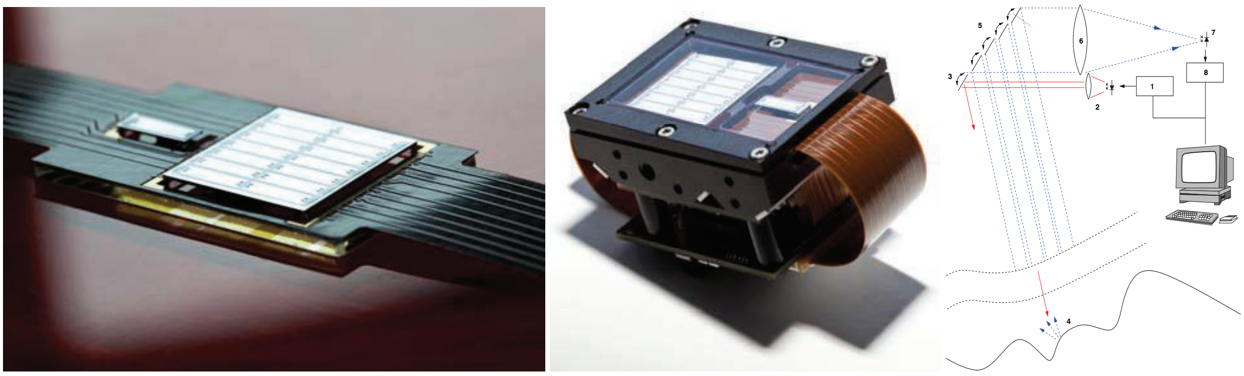

Fig. 9: MEMS scanner module for 3D TOF LIDAR systems, a) segmented scanner array preassembled chip on on bord, b) synchronized scanner module LAMDA with large receiver aperture, c) shematic setup of MEMS based TOF LIDAR system [12]

7 Summary

Micro scanning mirrors are widely used respectively developed for large variety of applications from consumer and telecom up to medical applications. Fabrication of micro scanning mirrors is based on a fully CMOC compatible bulk micromachining process. 1D and 2D scanning mirrors were designed and fabricated as well as scanning gratings and translation mirrors. IPMS presented in this paper the coustomer friendly and cost efficient technological platform VarioS, which allows customers to receive customised MEMS scanner demonstrators within a few weeks time at significant lower costs. The versatility of micro scanning mirrors was demonstrated by means of selected applications: e.g. an ultra compact VGA projector, a SVGA micro laser camera for endoscope applications, a scanning photon microscope, a large aperture MEMS scanner module developed for 3D laser disctance measurement.

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