Increasing MEMS micromirror line-scan rates through 3D-printed micro-optics

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***Abstract*—Line-scan rates of mechanical scanners are in general limited to <100 kHz for scan mirror apertures of up to 1 mm. We present work to increase the line-scan rate of a MEMS micromirror beyond this through a scan multiplication unit consisting of a mirror, a cylindrical lens, and a 3D-printed cylindrical microlens array with 1 mm pitch and 2.5 mm effective focal length. Scan rates of up to 635 kHz at the scan line centre are demonstrated with seven array lenslets, with the compact multiplier having the potential to achieve over 1 MHz line-scan rate using higher element numbers.**

Keywords*— *MEMS scanner, 3D-printed optics, scan multiplier unit, fast line scan

I. INTRODUCTION

Fast optical scanners are employed in applications ranging from supermarket checkouts, over LIDAR and flow cytometry to biomedical imaging. While the fastest scan technologies employ acousto-optic deflectors, their wavelength dependence, high RF power requirements and smaller scan angles compared to mechanical scanners mean most applications still employ mechanical movement scanners. Mechanical scanning principles include galvanometric mirrors, rotating Risley prisms, polygon scanning mirrors and MEMS micromirrors. While most of these have design variations that allow quasi-static scan positioning, the highest scanning speeds are achieved when actuating at mechanical resonances of the scanner. Each of the mentioned implementations has their unique advantages, but all have a limitation in their maximum scan speed based on material properties and their size, with larger structures of higher mass having inherently reduced resonance frequencies and scan speeds [1]. MEMS scanners have the advantage of a reduced size and mass, which allow resonance scan frequencies to be pushed up to several 100 kHz, albeit with small mirror sizes <500 µm diameter [2]. In most applications, mirror diameters of 1 mm or larger are required, which therefore reduce the maximum achievable scan frequencies to below 50 kHz, with MEMS scanners providing the highest resonance speeds.

To increase scan frequencies further, a simple, scalable and elegant approach has been recently shown that trades off scan angle for movement frequency through a scan multiplication unit [3] consisting only of a scan lens, a microlens array and a mirror. This has shown line scan repletion rates of >500 kHz with a 5 mm diameter galvanometer, aimed at applications in two-photon microscopy. In this work we will build on the demonstrated concept and make use of a MEMS resonant scanner with 27.8 kHz resonance frequency and a 3D-printed microlens array, based on previously demonstrated 3D-printed optics manufacturing approaches [4]. This will allow a compact and low-cost scan unit that enables line scan frequencies approaching 1 MHz.

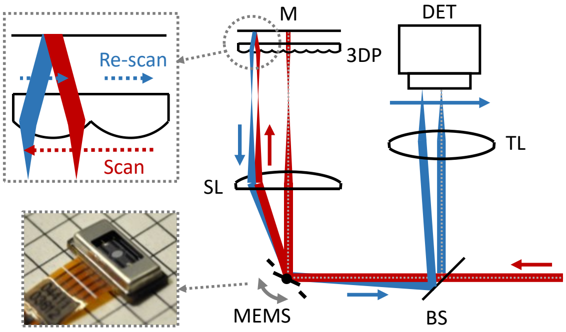

Fig. 1. MEMS scan unit schematic. The full MEMS angular scan gets converted into multiple re-scan parts with opposite scan direction. BS: broad band beam splitter, SL: cylindical scan lens, TL: tube lens, 3DP: 3D-printed cylindrical lens array, M: silver mirror, DET: fast photodiode detector.

II. SYSTEM OVERVIEW

The scan unit and overview of the experimental setup to verify system performance is shown in Fig. 1. An incoming laser beam enters the scan multiplier unit through a beam splitter (Edmund Optics #43-817, 25R/75T, 25 mm diameter) and undergoes a double pass through the unit. The commercial MEMS scanner (Ultimems UM-6002F) with 1 mm mirror diameter creates a scan line that is collimated at a cylindrical scan lens with focal length of 25 mm (Thorlabs LJ1810L1-A). A 3D-printed cylindrical microlens array with effective focal length of 2.5 mm forms a 4f configuration with the scan lens, with a silver mirror placed in the focal plane of the microlens array. The reflected light returns through the microlens array and scan lens as a collimated beam onto the MEMS. By scanning over the microlens array, each lenslet creates a scan with an angle depending on the diameter of the lenslet element and focal length of the scan lens. Importantly, all lenslet re-scans are copies of each other and therefore create a multiplication of an individual element scan, with identical scan direction (see inset Fig. 1). The output of the scan unit gets reflected by the beam splitter and focused by a tube lens (Thorlabs AC254-125-A) onto a pair of fast 2GHz photodetectors (Thorlabs DET025A).

III. SCAN SYSTEM ELEMENTS

A. 3D-printed lenslet array

The cylindrical lenslet array used in this work is 3D-printed using a consumer grade low-cost printer (Elegoo Mars 2) together with post-processing steps to create optical

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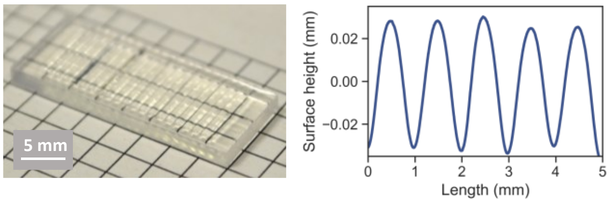

Fig. 2. Lens array image and surface profile after post-processing.

quality surfaces [4]. The 1 mm diameter lenslets have a design radius of curvature of 1.26 mm on top of a 2 mm backing part, with effective focal length of 2.5 mm. The array consists of 20 lenslets, with an overall part width of 25 mm.

The arrays were printed using a 10 µm step height with a transparent clear resin (Formlabs Clear resin) which has a refractive index of 1.52 after printing. To smooth out the residual surface staircase effects through the pixilation of the printer, a spin-coating post-process step was undertaken. The lenslet curved surface was coated with a secondary clear resin (Vida Rosa) using a gradual ramp up to 6000 rpm spin speed for 40 seconds. After spin-coating the array was cured with UV light for 10 min. A second coating step for the flat back-surface of the array was undertaken following the steps in [4].

The surface of the array was characterised using a stylus contact surface profiler (KLA-Tencor Alpha Step) with 5 µm tip radius. Line-scans over a 5 mm length along the cylindrical lens array were taken (see Fig. 2), showing a smooth surface finish with radius of curvature of the lenslet central 80% area of 1.37 ± 0.07 mm. The surface roughness is calculated as less than 45 nm. The flat side of the 3D-printed array was additionally evaluated, showing a surface roughness of less than 10 nm.

B. MEMS scanner characterisation

A 2-axis commercial MEMS scanner (Ulitmems UM-6002F) with 1 mm mirror diameter and electrostatic actuation of a resonant and quasi-static scan axis is used in our scan multiplier unit. Only the resonant axis is actuated in this case, using a Rigol DG1022Z signal generator and FLC A400 20x voltage amplifier to reach MEMS drive voltages of up to 200 V. An offset square-wave drive signal is applied to one side of the fast, resonant scan axis using twice the movement frequency. The resulting optical scan behaviour is shown in Fig. 3, with a maximum reachable scan angle of 35° at 55.55 kHz actuation (and 27.78 kHz movement) frequency. The scanner does include a hysteresis behaviour, requiring on-switch of the movement above 55.8 kHz for the highest drive voltage.

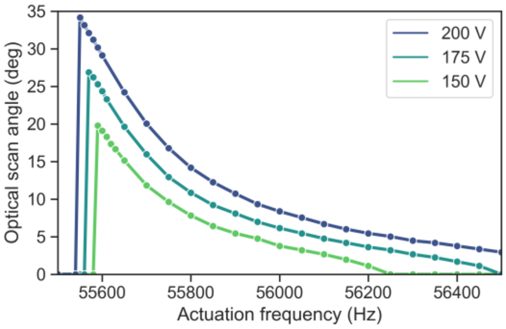

Fig. 3. MEMS scanner resonance behaviour with varying excitation voltages.

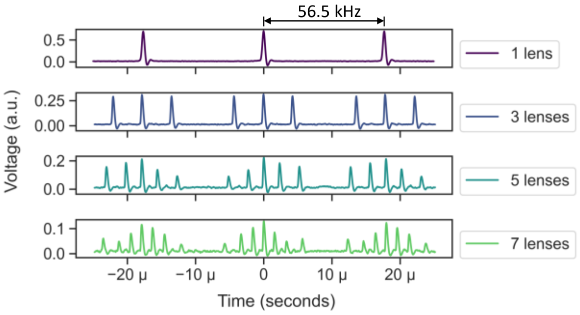

Fig. 4. Photodiode readout of the scan line after the scan multiplication unit, with the diode placed at the centre of the scan.

IV. SCAN UNIT CHARACTERISATION

To demonstrate the scan frequency amplification, a MEMS actuation voltage of 200 V and a selection of MEMS drive frequencies of 56.5 kHz, 56.2 kHz, 55.7 kHz, and 55.6 kHz are chosen. The resulting scan angles of 2.9°, 5.4°, 20°, and 29° fully fill 1, 3, 5 or 7 lenslet arrays. The output of the scan multiply unit is recorded on a 2 GHz photodiode which is placed at the centre of the scan line after the tube lens, with resulting time traces shown in Fig. 4. The sinusoidal resonance movement of the MEMS leads to a variable spacing of the centre of the multiplied scan lines, with faster centre point spacing at the centre lenslets compared to the spacing where the MEMS changes movement direction. For the four cases this leads to a maximum centre scan line repetition frequency of 56.5 kHz, 232.6 kHz, 434.8 kHz, and 635.1 kHz when looking at the re-scan lines between the centre lenslet and its neighbours.

V. DISCUSSIONS AND CONCLUSION

The combination of a resonant MEMS scanner and 3D-printed microlens array shows the expected scan frequency multiplication by a factor of up to seven. While this initial demonstration only used up to seven cylindrical microlenses, a combination of a better matched cylindrical scan lens, relative to the maximum MEMS scan angle, will allow reaching frequencies in excess of 1 MHz if 20 lenslets are used. We will show variations of lenslet size and scan lens combinations and explore unique opportunities through 3D-printed optics design to reduce field curvatures of the scan assembly.

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