Exploration of 3D-printed lenses in a confocal MEMS microscope concept

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***Abstract*—We present the use of affordable 3D-printed lenses as critical elements in a small-footprint confocal MEMS microscope concept. Their excitation and imaging performance will be compared to commercial standard glass lenses.**

Keywords—MEMS micromirror, 3D-printing, confocal microscopy

I. Introduction

Optical microscopy is one of the key tools in biological research. In the last decade developments of advanced microscope concepts have accelerated, looking at ever increasing resolution in super-resolution approaches [1] and high throughput imaging of large specimens and intact “model animals” through advancing light-sheet microscopy approaches [2]. These exciting developments have however come at ever increasing price tags of systems. To address this and improve both equitable access and sustainability of microscope availability, open hardware routes have developed, based in part on 3D-printed opto-mechanics and assemblies to allow researchers and end-users to create their system in-situ and allow access in low-resource settings [3]. While these approaches mostly include mechanical parts, separate developments in creating low-cost 3D-printed optical elements have been undertaken, making use of the availability of affordable consumer grade 3D-printers with ever increasing resolution and enable the leveraging of the inherent free-form design possibilities.

While a range of approaches for 3D-printing optical parts have been demonstrated [4-6], only recently they have been integrated and demonstrated in fluorescence microscopy approaches [7]. To further explore their applicability in creating advanced microscopy approaches, we will here be looking at integrating affordable 3D-printed optical elements in a miniaturised confocal microscopy concept created as test bed and including a MEMS micromirror for beam steering to leverage the full potential of miniaturisation and integration in a small footprint package.

II. 3D-printed Lenses

A. Fabrication process

The process to create the 3D-printed lenses used for evaluating their applicability in the confocal microscope concept is based on our recent work [7]. We are using a consumer grade LCD 3D-printer (Phrozen Sonic Mini 8K S) in combination with a transparent photopolymerization resin (Anycubic High Clear, refractive index 1.50-1.51) as base, with a 0.1 mm thick diffusion sheet added between the LCD and resin vat to reduce inhomogeneities in the individual print layers originating from shadowing by the edges of the individual LCD pixel creating the print layer structures. The lens designs are printed flat on the build base, with an in-plane pixel resolution of 22 µm and a layer step height of 10 µm. After printing the parts are cleaned in isopropanol alcohol, before undergoing a post-process spin-coating step to create optical quality surfaces. A thin layer of a high viscosity, fast curing secondary resin (Vida Rosa UV resin, refractive index 1.51) with identical refractive index to the used base resin [8] is spun onto the curved side of the plan-convex lenses and cured under UV illumination. For the flat side a thin layer of the base resin is spun onto a microscope slide followed by placing the lens on the slide, removing of residual air bubbles in the resin through a degassing step and curing of the lens and microscope slide combination. As final step the lens is released from the slide through a thermal cycle using a small amount of cooling spray. A qualitative comparison of the surface finish before and after the post-processing step is shown in Fig. 1A and 1B respectively.

B. Characterisation

The surface quality and shape of the 3D-printed and post-processed lenses is evaluated using a contact stylus profiler with sub-nanometer vertical resolution (Tencor Alpha Step IQ). Line profiles over the centre of the printed lenses are taken for elements with and without the post-process coating step (see Fig. 1C), showing the expected staircase profile being smoothed to optical quality surfaces with roughness of Ra ~ 20 nm over the 4.5 mm scan length, equivalent to > λ/20 for the laser excitation wavelength of 488nm of the confocal microscope concept.

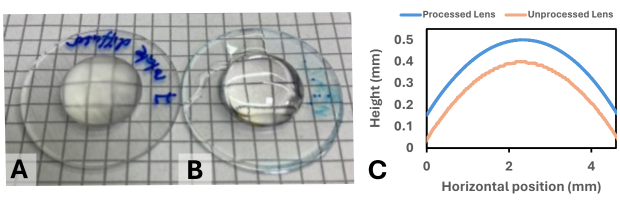

Fig. 1:3D-printed 12.7mm diameter lenses A) directly after printing and B) after post-processing. C) Surface profile of both pre- and post-processed lenses.

III. Microscope Design

To evaluate the applicability of the 3D-printed lenses in a compact microscope setup, a custom small footprint confocal microscope was created, using a 2 mm diameter 2D MEMS micromirror (Mirrorcle A7M20.2) as central element next to the 3D-printed optics. The simple setup is shown in Fig. 2.

A low cost 488 nm diode laser (Odicforce A-B60F) is single mode fibre coupled, filtering the output to a TEM00 Gaussian beam profile, and uses as excitation source in the

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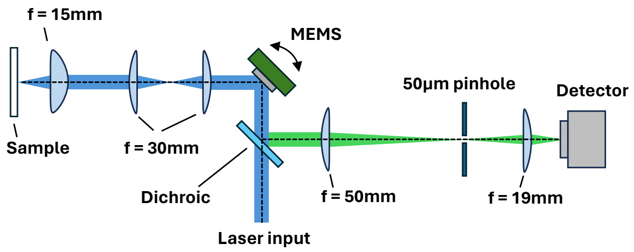

Fig. 2: Schematic of 3D-printed confocal MEMS microscope setup

setup. The excitation is collimated with a beam diameter of 1.95 mm and guided through a short-pass dichroic mirror (Thorlabs DMSP505) onto the MEMS mirror. The scanned beam is guided through a 30 mm achromatic scan lens (Thorlabs AC127-030-A), followed by a further lens pair to create the telecentric excitation in the sample. A second 30 mm achromat is acting as tube lens, followed by the f = 15 mm 3D printed lens acting as objective lens and focusing the illumination into the sample mounted on an axial translation stage (Thorlabs MTS25/M-Z8).

The generated fluorescence is collected by the same lenses and de-scanned by the MEMS mirror. A 50 mm focusing lens (Thorlabs AC254-050-A) is focusing the collected signal through a 50 µm pinhole (Thorlabs P50HK), with a 19 mm lens (Thorlabs AC127-019-A) collimating the beam and guiding it to a CMOS camera (IDS 3060CP) as test detector.

IV. Results

To evaluate the excitation performance of the 3D-printed objective lens the beam profiles through the focus were re-imaged onto a CMOS camera with 0.32 µm effective pixel size. The axial propagation and focal depth were measured using cross-section images at 10 µm steps through the focus. A control setup using a commercial N-BK7 glass lens with equivalent focal power and shape was used as benchmark, with the resulting xz-propagation through the focus and xy focal plane of the reference objective lens shown in Fig. 3A. The equivalent xz-propagation and xy cross-section using the 3D-printed objective lens is shown in Fig. 3B. The in-focus cross-sections show a FWHM spot size of 5.2 µm for the glass lens and 5.7 µm for the 3D-printed lens, indicating a good match of the focal powers and an effective numerical aperture (NA) for the setups of 0.048 and 0.043 respectively. The propagation in both cases shows expected spherical aberrations from the simple plan-convex objective lens geometry. Additional aberrations can be seen in the lateral cross-section of the 3D-printed lens focal spot, adding minor intensity wings to the profile.

To further evaluate the confocal microscope response, a microscope slide with a thin fluorescent coating was used as target and placed in the focal plane of the setup. The resulting in- and out-of-focus profiles with and without the confocal pinhole in the beam path are shown in Fig. 4, highlighting the sectioning ability. While the low NA of the test setups is limiting the sectioning ability, a multi-lens objective for increased resolution and NA is being integrated, enhancing the inherent advantages of the sectioning ability in the confocal setup.

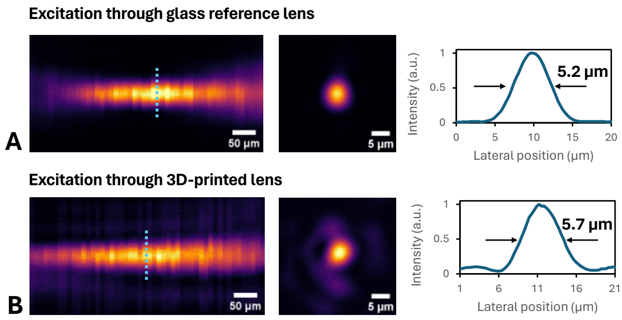

Fig. 3: Sample excitation beam profile over FOV

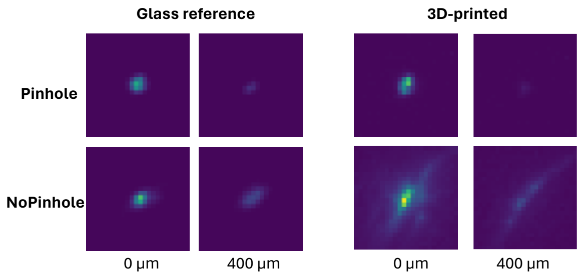

Fig. 4: Fluorescence response on the detector for the glass reference lens and 3D-printed lens configuration, with in-focus (0 µm) and out-of-focus (400 µm) responses.

Next to this initial confirmation of comparable illumination profiles and confocal sectioning between the 3D-printed and glass objective lens we will also investigate and show the full imaging performance and the impact of replacing further glass lenses with 3D-printed equivalents.

Data Availability

All data underpinning this publication are openly available from the University of Strathclyde KnowledgeBase at https://doi.org/10.15129/5f6638ca-907c-4b4b-989f-ce1e474ee111

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