Development of 3D-printed micro-lenses at the edge of waveguides of flow cytometry and optical coherence tomography photonic integrated circuits

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INTRODUCTION

Modern medicine faces critical challenges in diagnosing diseases like cancer and cardiovascular disorders. Extracellular vesicles (EVs), nanoscale particles involved in cellular communication, are promising biomarkers. Detecting and analyzing EVs in blood reveals crucial insights into disease progression but is challenging due to their small size and low concentrations.

A multi-sensing biophotonic platform with photonic integrated circuits (PICs) for flow cytometry (FCM) and optical coherence tomography (OCT) enables the detection of EVs as small as 140 nm [1][2]. This study focuses on 3D-printed micro-lenses, which consist essential optical components within the platform, optimized for 520 nm, 638 nm, and 790 nm wavelengths. These lenses facilitate precise light manipulation and efficient coupling, achieving optical losses as low as 0.7 dB, highlighting their potential for advancing biomedical diagnostics.

METHODS

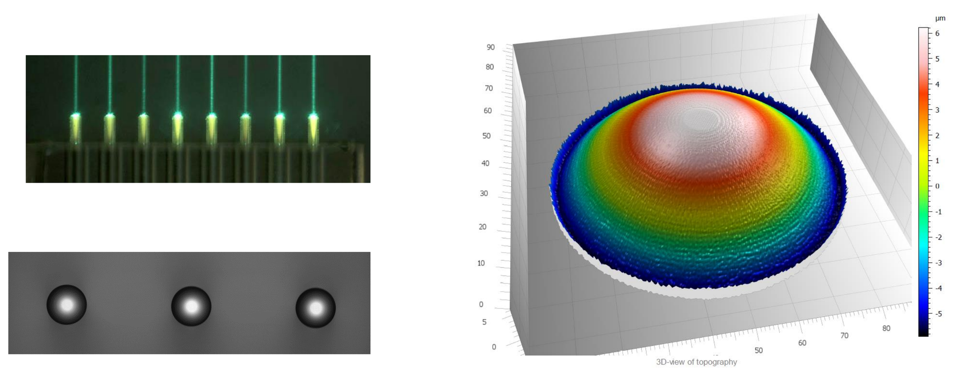

Fig. 1: Example of 3D printed lenses from a related experiment: a) photography of a lens array printed on fibre array's facet, b) confocal microscope image presenting top view of three lenses in an array, c) confocal microscope surface analysis for an individual lens in an array

The micro-lenses were designed in Zemax software, optimizing their curvature, material properties, and coupling efficiency for 520 nm, 638 nm, and 790 nm wavelengths. Fabrication used two-photon lithography (Nanoscribe Quantum X Align [2]) with over 99% structural accuracy and surface roughness below 20 nm. Checkerboard fiducials ensured precise placement on photonic chips. Lenses were printed at the edges of Fiber Array Units (FAUs) and PICs. Quality was assessed by comparing theoretical 3D models with measured geometries using confocal microscopy. Testing measured coupling losses and beam profiles, while reliability was confirmed through thermal annealing and mechanical shear tests.

SIMULATION STUDY

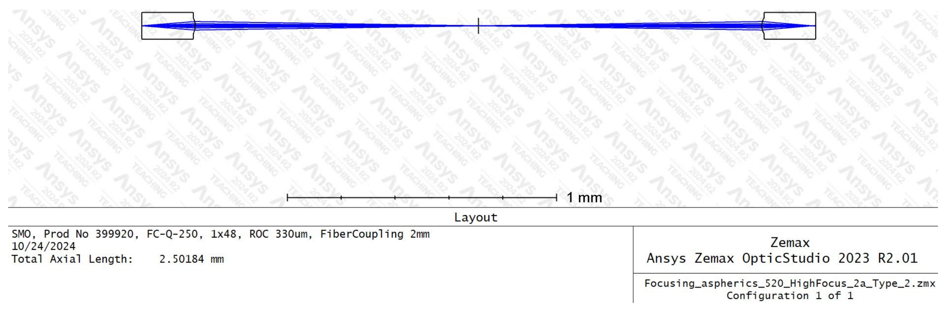

Fig. 2: Simulation setup in ZEMAX for the design of the lenses

The simulation of the micro-lenses was carried out using Zemax software to evaluate and optimize their optical performance. The lens designs were tailored for operational wavelengths of 520 nm, 638 nm, and 790 nm and were simulated with a fixed 2 mm distance, as required for the FCM and OCT applications.

During simulations, adjustments were made to lens curvature and dome height to maximize coupling efficiency. The finalized designs were then prepared for fabrication and testing.

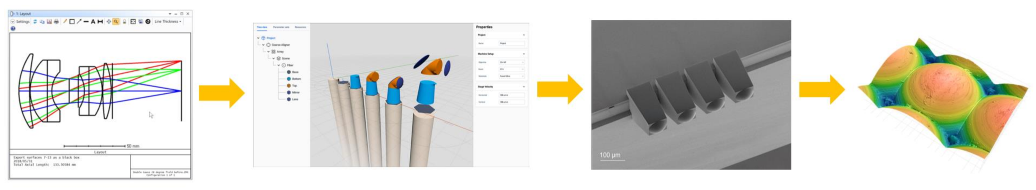

Fig. 3: Flowchart of 3D lens fabrication

EXPERIMENTAL RESULTS

The fabricated micro-lenses were tested to evaluate their optical performance at operational wavelengths of 520 nm, 638 nm, and 790 nm. The 520 nm and 638 nm lenses were tested at their designated wavelengths, while the 790 nm lenses used an 850 nm laser. For every wavelength, the setup included two FAUs, each containing eight identical lenses. During the testing procedure, three lenses in one FAU were used to emit light, while all eight lenses in the second FAU acted as receivers.

The 3x8 different couples were examined to ensure higher reliability. Alignment was performed using 6-axis flexure stages, though the exact distance between lenses could not be measured.

The results demonstrated coupling losses of 0.3 dB (93% efficiency) for 520 nm lenses, 0.4 dB (91% efficiency) for 638 nm lenses, and 0.7 dB (85% efficiency) for 790 nm lenses.

Occasionally, one or two outliers were observed, primarily at the outermost lenses.

These deviations are suspected to result from alignment limitations, and less likely, fabrication imperfections or minor damage to the lenses.

The overall results confirm the high reliability and repeatability of the micro-lenses. Additionally, the 790 nm lenses are expected to perform better when tested at their intended wavelength, as the current measurements were conducted using an 850 nm laser.

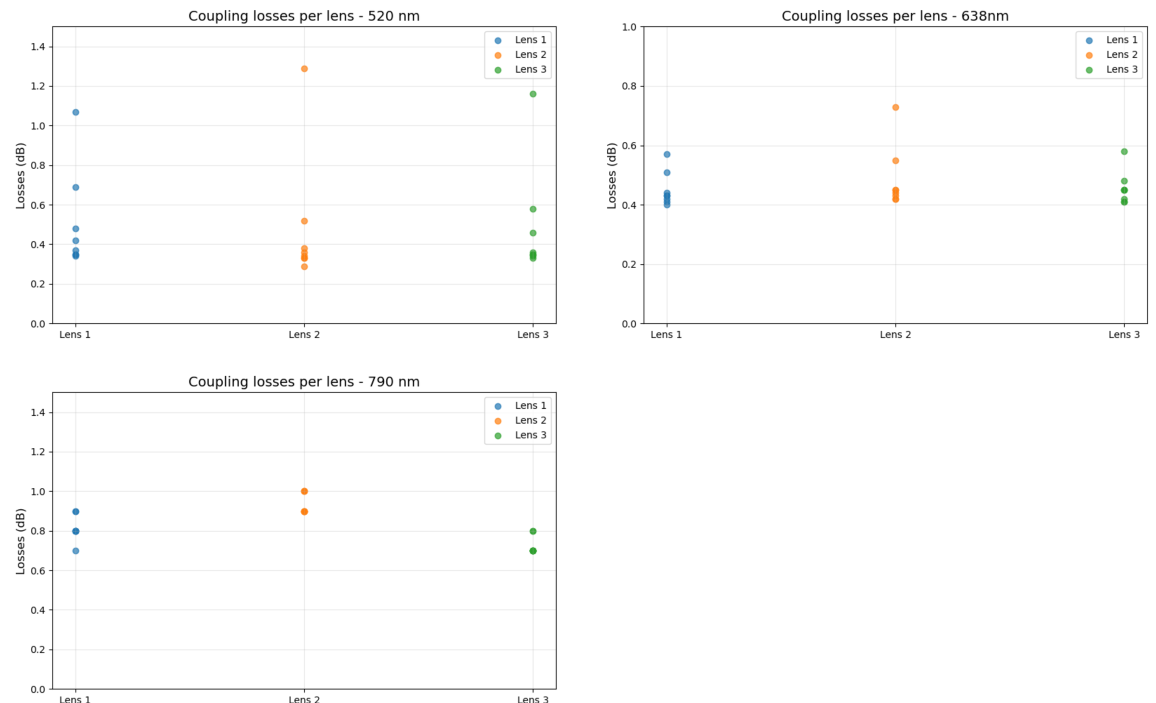

Fig. 4: Experimental results: coupling losses for micro-lenses at 520 nm, 648 nm and 790 nm

CONCLUSIONS

This study demonstrated the successful design, fabrication, and testing of 3D-printed micro-lenses for photonic integrated circuits. The lenses achieved coupling losses of 0.3 dB, 0.4 dB, and 0.7 dB for 520 nm, 638 nm, and 790 nm (tested at 850 nm), respectively, with high repeatability. Reliability tests confirmed their structural and optical stability under thermal and mechanical stress.

These findings highlight the potential of 3D-printed micro-lenses to improve light manipulation in compact and cost-effective photonic systems for biomedical diagnostics.

REFERENCES

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3. Nanoscribe Quantum X Align: High-resolution 3D printer: //www.nanoscribe.com/en/products/quantum-x-align/

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