Bringing PMMA free-form optics fabrication to the desktop: a low-cost system based on cold atmospheric plasma etching

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ABSTRACT

An inexpensive integrated system for prototyping free-form optical elements made of plastic/glass, intended for laser beam shape transformation, is presented. The system combines directed etching with cold atmospheric plasma, a white light interferometer for measuring the surface shape, and a post-processing method that achieves a roughness of less than 50 nm. Most components are assembled from readily available inexpensive parts, while others are 3D printed, and the entire set-up is assembled on a consumer 3D printer platform. As a demonstration, lenses made of PMMA with an aperture of 10 mm were produced to transform a Gaussian beam with a diameter of 2 mm (wavelength of radiation 532 nm) into beams of various shapes: square, circle, star (top-hat).

Keywords: free-form optics, plasma etching, confocal profilometry

1. INTRODUCTION

Beam shaping—the process of tailoring intensity and phase distributions of laser radiation—is essential for applications in laser micro-machining, optical trapping, microscopy, display technologies, and biomedical imaging [1, 2]. Conventional refractive or diffractive optics often fail to provide the required flexibility, which stimulated the rise of free-form optics—optical elements with non-rotationally symmetric surfaces [3,4].

Despite advances in design algorithms [1, 4], the widespread use of free-form optics remains limited by the complexity and cost of fabrication methods, such as diamond turning, lithography, or laser ablation. These methods demand clean room infrastructure and expensive equipment, restricting the technology to specialised facilities.

At the same time, a trend towards democratisation of optical prototyping has emerged, driven by open-hardware platforms, 3D printing, and DIY (do it yourself) approaches. This raises the question: can free-form optics fabrication be brought to the desktop level with sufficient accuracy for real optical research?

Our work demonstrates a low-cost integrated platform for prototyping thin free-form polymer optics, combining atmospheric plasma jet etching, *in situ* confocal profilometry, and post-processing for optical surface quality.

2. METHODS

a. System architecture

The platform is based on a modified desktop 3D printer used as an open CNC stage. The etching module is a custom-built atmospheric plasma jet (APPJ) optimised to deliver a narrow, low-temperature plasma plume. For surface characterisation, we integrated a confocal profilometer with sub-micron vertical resolution on the same support as the plasma nozzle, ensuring rigid alignment between fabrication and measurement.

b. Exposure control

A target surface profile is translated into an exposure map, defining local etching times. Since the plasma spot has a Gaussian removal function (FWHM ≈ 440 μm), calculating the map corresponds to solving an inverse convolution problem. Regularisation (*e.g.*, Tikhonov) is applied to obtain stable solutions.

The printer executes these maps as variable-speed G-code trajectories (60–2000 mm/min), providing proportional depth control. A 10×10 mm element typically requires ~50 passes and 2–3 hours of fabrication.

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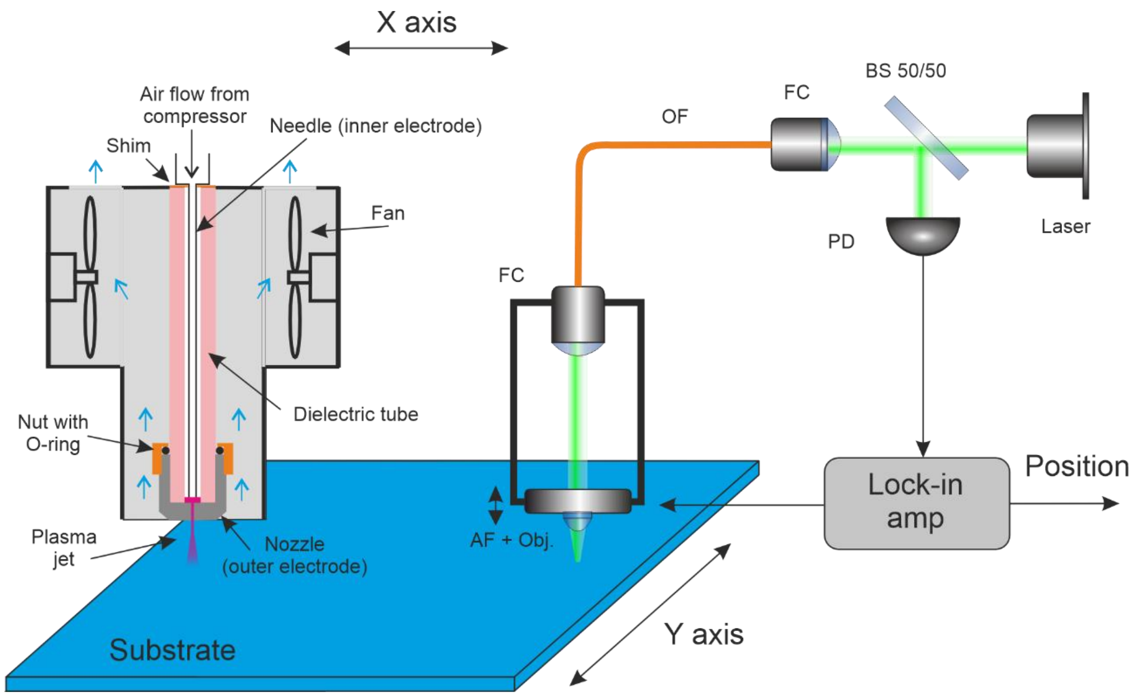

Figure 1. Schematic of the integrated system combining a desktop 3D printer, plasma jet generator, and confocal profilometer. FC – fibre collimator, OF -optical fibre, PD – photodetector, AF + obj. – voice-coil actuated autofocus module with objective, BS – beam splitter.

c. Post-processing

Etching introduces surface roughness at a sub-micron scale. To achieve the required optical quality, we applied a two-step smoothing protocol: (i) annealing at 60–70 °C and (ii) short acetone vapour exposure. This reduced RMS roughness below ~50 nm, sufficient for phase-controlled applications.

d. Mask calculation

We tested three approaches for calculating free-form phase masks:

1. Monge–Ampère equation (efficient for paraxial intensity mapping) [1].
2. Optimal transport morphing + Gerchberg–Saxton (smooth solutions beyond paraxial limits).
3. Heat-equation morphing + Gerchberg–Saxton (stable convergence for complex profiles) [5].

3. RESULTS

We fabricated free-form PMMA phase masks to demonstrate the capabilities of the proposed system. In the experiments, a Gaussian beam with a radius of 2.3 mm at a wavelength of 532 nm was transformed into a square and circular top-hat profiles at a propagation distance of 250 mm. The measured surface profile of the fabricated mask closely matched the calculated design, with deviations remaining within sub-micron accuracy after correction of mechanical distortions introduced by the printer. Optical testing confirmed that the transformed beam profile in the target plane exhibited a uniform intensity distribution in good agreement with simulations. To ensure adequate optical quality, we applied the developed post-processing protocol, which reduced the surface roughness to below 50 nm. This level of smoothness was sufficient to minimise scattering losses and to demonstrate that the fabricated free-form elements operated as functional phase masks.

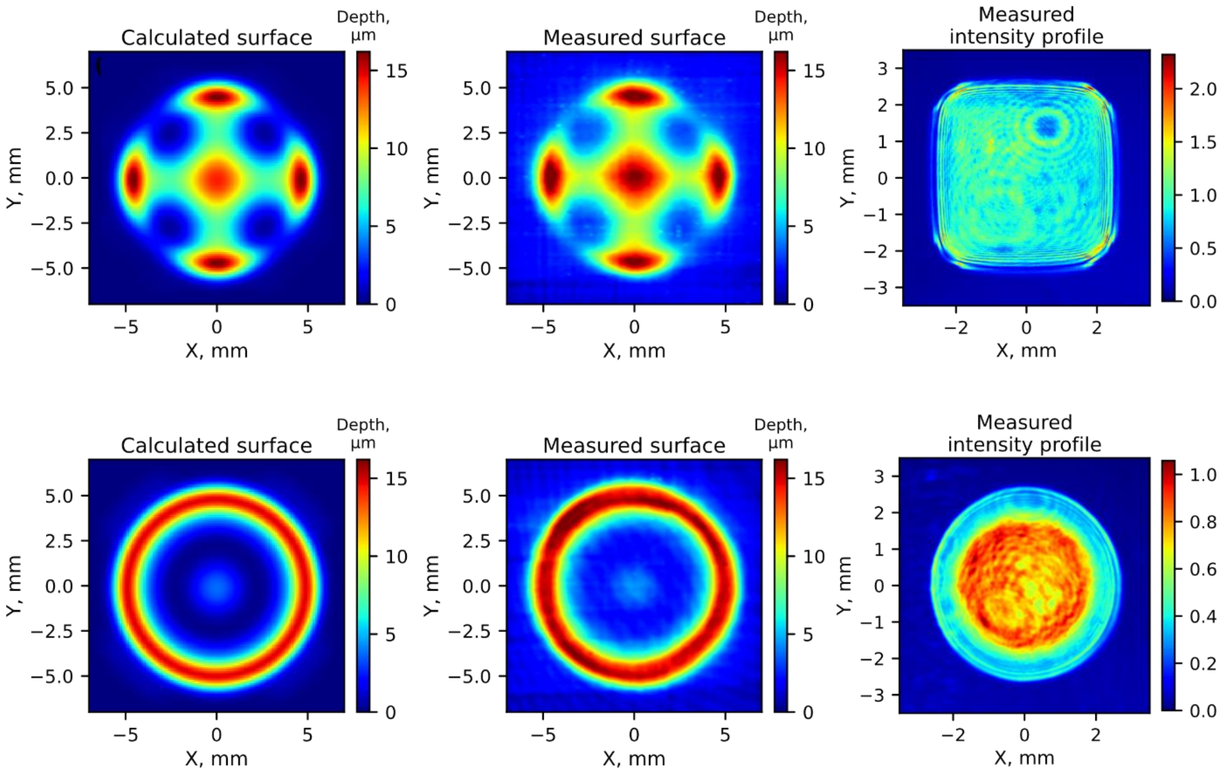

Figure 2. Example: calculated *vs* fabricated phase mask profile and corresponding transformed beam profile for square and circular top-hat.

4. DISCUSSION AND CONCLUSION

The presented results demonstrate that fabrication of functional free-form optical elements is feasible using an inexpensive, desktop-scale platform that integrates cold atmospheric plasma etching, open-hardware CNC motion, and *in situ* confocal profilometry. The combination of these components enables a complete design–fabrication–characterisation cycle, providing both the precision required for beam shaping tasks and the flexibility to iteratively adjust the fabrication process. Importantly, the system achieves this while relying on readily available components and minimal consumables, which reduces the overall cost by more than two orders of magnitude compared to conventional technologies.

Successful transformation of a Gaussian beam into a uniform square top-hat profile illustrates the ability of the platform to reproduce complex optical surfaces with sub-micron accuracy and optical-quality surface roughness. These findings support the broader trend of democratisation in optical technologies, where accessible tools enable laboratories, educational institutions, and small research groups to prototype advanced optical elements outside specialised facilities. Looking ahead, the transition from polymer substrates to more stable optical materials such as glass appears promising, particularly when combined with sol–gel techniques compatible with the low-cost, desktop approach. This extension would further increase the robustness and applicability of the method while preserving its affordability and accessibility.

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