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Laser Polishing Using Quasi-Beamforming to Enhance Optical Quality of Miniaturized Optics

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Abstract

Laser-based manufacturing of optics is a promising technology with significant potential for the efficient production of high-precision and complex optical components. At the Institute for Microtechnology and Photonics (IMP), we focus on the selective laser etching (SLE) process chain combined with laser polishing, particularly for miniaturized optical elements. This paper presents an enhanced laser polishing strategy based on a Quasi-Beamforming approach, developed as an extension of the One-Shot polishing strategy. The method dynamically modulates the energy input via high-speed galvanometric scanners to generate a tailored "Sombrero" thermal distribution. By redistributing thermal energy from the center toward the edges, a quasi-uniform thermal influence is achieved across the entire convex lens surface. This controlled heating minimizes mid-spatial frequencies and improves both surface roughness and shape accuracy—especially at the lens periphery. Experimental results demonstrate that the method not only enhances optical quality but also improves energy efficiency by enabling shorter exposure times and reducing thermal stress within the material. The approach is particularly suitable for rotationally symmetric mini-optics such as convex lenses, where conventional methods often fail to provide uniform laser polishing.

Keywords: laser polishing, selective laser etching, mini optics, CO_2 laser, surface roughness, asphere, non-contact processing, beamforming

1. Introduction

Conventional manufacturing techniques for optical components involve mechanical grinding and polishing, which introduce issues such as tool wear, debris, and limitations in fabricating complex geometries. Laser-based techniques have emerged as a powerful alternative, offering contact-free processing and high reproducibility [1-3]. In previous work [4], a novel laser process chain was introduced for shaping and polishing aspherical micro-optics, demonstrating strong potential for wafer-level integration.

In a related study [5], a One-Shot laser polishing strategy was implemented using an 8 mm Gaussian beam ($1/e^2$) to polish miniaturized optics. While this approach effectively suppressed mid-spatial frequencies by avoiding scanning, it led to higher surface roughness values in the edge region of the lenses compared to the center, due to the non-uniform intensity distribution of the Gaussian beam. The One-Shot method relies on a Gaussian beam profile that leads to significantly reduced energy density in the edge regions of convex surfaces. Attempts to compensate by using an oversized Gaussian beam—even larger than the lens itself—were only partially successful, as the temperature distribution remained non-uniform. This resulted in poor polishing in the edge region and excessive energy input at the center.

Furthermore, when polishing convex surfaces, the laser beam typically impinges perpendicularly only at the center of the lens. Toward the edge region, the local surface normal becomes increasingly tilted relative to the beam axis. As the curvature of the surface increases, a higher energy input is required to achieve the same thermal effect, since the angle between the incident beam and the surface normal increases. Therefore, more laser power is needed in the edge region of convex surfaces to compensate for the reduced effective energy deposition.

A Diffractive Optical Element (DOE) with a nominal diameter of 4 mm was also tested, generating a cylindrical top-hat intensity profile. Although this profile within this diameter was intended to provide a uniform power distribution, intensity fluctuations of up to 15% were observed across the region assumed to have a constant intensity level. These variations led to non-uniform heating, resulting in an inhomogeneous thermal distribution. As a result, the polishing performance was unsatisfactory, with a mismatch between the intended and the actual energy delivery.

To overcome these limitations, we developed a new Quasi-Beamforming strategy. This approach replaces conventional scanning patterns with high-speed circular motions of galvanometric mirrors, generating a dynamic Sombrero-shaped thermal profile. As a result, energy is distributed more uniformly across the surface, minimizing mid-spatial frequency artifacts while enhancing energy efficiency and lowering the thermal load [6].

2. Experimental Setup

To evaluate the effectiveness of the Quasi-Beamforming strategy for laser polishing of miniaturized optical components, a dedicated experimental setup was established. The procedure involved the fabrication of biconvex aspherical lenses via SLE, followed by thermal surface finishing using a CO_2 laser. The setup was designed to ensure high reproducibility, surface uniformity, and compatibility with wafer-level manufacturing. The key components of the experimental configuration are outlined below.

Materials: Fused silica wafers (double-side polished), 100 mm in diameter and 1 mm thick. Each wafer contains up to 112 miniaturized biconvex lenses with an aspherical front surface.

Lens Geometry: The miniaturized lenses fabricated in this study are rotationally symmetric and feature a biconvex asphere geometry. The front surface has a conic constant of CC = –0.875 and an aspheric radius of R = 1.387 mm, while the rear surface has a stronger curvature with R = 5.63 mm. The total lens diameter is 1.6 mm, and the central thickness is 0.6 mm. The lens design is identical to the one presented in [5], where the polishing process focused primarily on the rear surface. The geometric parameters of the lenses are illustrated in Fig. 1. After the polishing process, the individual lenses can be separated from the wafer via laser cutting.

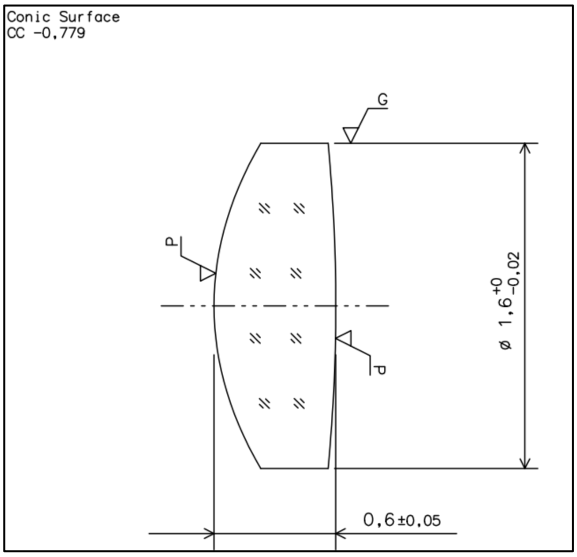

Fig. 1. Technical drawing of the miniaturized biconvex aspherical lens used in this study.

SLE System: Selective laser etching was performed using a LightFab 3D Printer operating at a wavelength of 1030 nm, with a pulse rate of 750 kHz and a pulse duration of 1 ps, focused through a 20× objective. Subsequent etching was carried out in 8 mol/L KOH at 80 °C [4].

Laser Polishing Setup: Laser polishing was performed using a CO_2 laser (λ = 10.6 µm, 98.3 W average power) with a defocused beam guided by a galvanometric scanner. The wafers were mounted on a heating plate at temperatures up to 600 °C.

New Strategy: The polishing uses a Quasi-Beamforming approach. A Gaussian beam with a diameter of 3 mm ($1/e^2$) was operated in continuous wave (CW) mode and scanned in circular motion using galvanometric mirrors. The scanning speed was set to 5 m/s, and the circular path had a radius of 1.1 mm. This circular motion was repeated 154 times, resulting in a total exposure time of approximately 213 milliseconds per lens. This exposure created a thermal Sombrero profile on the surface. The tailored energy input led to a quasi-stationary thermal field that enabled uniform polishing across the lens surface without introducing mid-spatial frequencies.

Measurement Tools: White light interferometry was performed using the Sensofar S Neox system and subsequently analyzed with MountainsMap software.

2.1. Illustration of the Quasi-Beamforming Strategy Using a 2 mm Gaussian Beam

To provide a clearer understanding of the Quasi-Beamforming mechanism, a thermal profile was experimentally recorded on a planar fused silica substrate under reduced laser power—lower than the levels typically used for polishing. This experiment was conducted using an infrared camera setup under exaggerated conditions to enhance the visibility of the resulting thermal effects. A Gaussian beam with a reduced diameter of 2 mm ($1/e^2$)—instead of the standard 3 mm—was used to emphasize the characteristic Sombrero-shaped temperature distribution. The scan speed was set to 5 m/s to ensure a quasi-stationary thermal field.

Figure 2a shows the thermal image, revealing the characteristic ring-shaped heat distribution. While the center remains comparatively cooler, a distinct high-temperature ring forms along the scanning radius. This pattern emerges from the circular galvanometric motion and confirms the generation of a quasi-stationary thermal field.

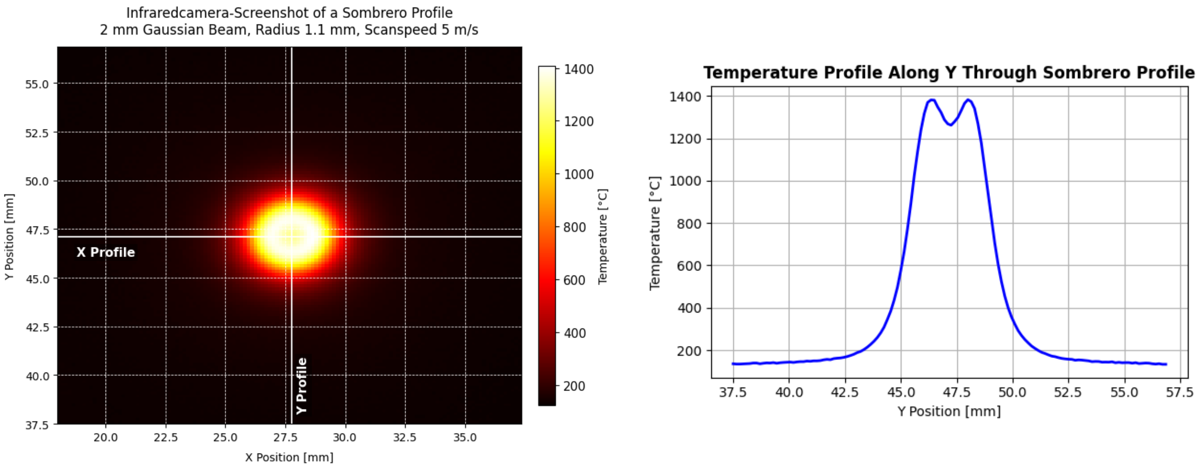

Fig. 2 (a) Infrared thermal image of a fused silica substrate exposed to a 2 mm Gaussian beam under reduced laser power, illustrating the characteristic ring-shaped heat distribution (Sombrero profile).
(b) Extracted temperature profile along the Y-axis, revealing a double-peak structure corresponding to the radial heat concentration induced by the circular scanning motion.

Figure 2b presents the extracted temperature profile along the y-axis. The characteristic double-peak structure highlights the concentration of thermal energy in a ring-shaped zone around the beam center. This tailored thermal input results in a homogeneous thermal influence across the convex lens surface, ensuring controlled energy delivery and minimizing thermal gradients.

The resulting Sombrero temperature profile plays a key role in minimizing roughness in the edge region and suppressing mid-spatial frequencies. By shifting the thermal load away from the center toward the edge region, the Quasi-Beamforming approach overcomes the fundamental limitations of conventional Gaussian or DOE-based strategies.

3. Results and Discussion

To systematically investigate the influence of the Quasi-Beamforming strategy on polishing performance, a full wafer containing 112 miniaturized biconvex aspherical lenses was fabricated using the SLE process. This array allowed for parallel testing of different laser parameters under identical material and geometric conditions. Figure 3 shows a image of the wafer, illustrating the arrangement of the lenses.

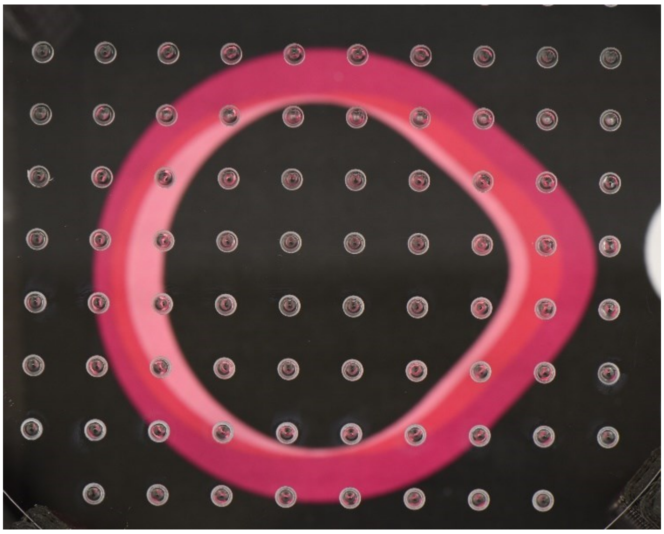

Fig. 3. Overview image of a polished wafer with biconvex lenses arranged in a grid pattern. Different laser parameters were applied across the array to identify optimal polishing conditions.

Each lens was subsequently analyzed via white light interferometry to quantify surface roughness and form deviation. This systematic evaluation revealed that the parameter configuration described in Chapter 2—involving circular scanning with a 3 mm Gaussian beam and a scan radius of 1.1 mm—yielded the best overall polishing result. In the following, this specific lens is analyzed in detail to assess the effectiveness of the Quasi-Beamforming strategy in terms of surface quality and shape fidelity.

Compared to the Gaussian-based One-Shot method, the Quasi-Beamforming strategy demonstrates significant improvements in both surface roughness and shape accuracy. The tailored thermal profile effectively addresses the challenge of polishing in the edge region by redistributing energy toward that area.

To understand the measurement layout, Figure 4 shows a white light interferometry (WLI) scan of the selected mini-lens. The colored rectangular areas mark surface roughness sampling positions, while the black horizontal line indicates the location of the cross-section used for form deviation evaluation.

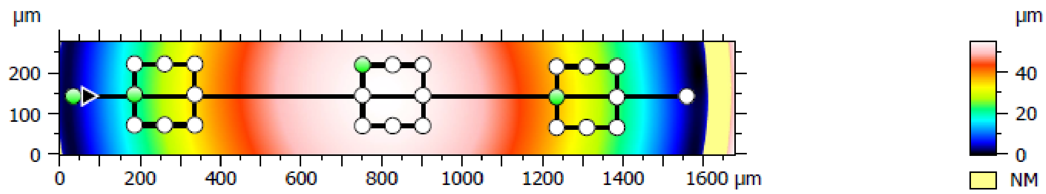

Fig. 4. WLI measurement of the selected mini-lens. Highlighted areas mark surface roughness sampling locations; the black line indicates the cross-section for form deviation evaluation.

Surface Roughness (Sq): Analysis of the WLI measurements (150 × 150 µm² areas) revealed a clear improvement in surface quality at both the center and the edge regions of the lens. Figure 5 presents representative roughness maps from the left edge region, center, and right edge region.

Whereas previous methods often resulted in surface roughness values exceeding 20 nm in the edge region of the lens, the Quasi-Beamforming strategy consistently achieved Sq values below 2.5 nm. Specifically, measurements showed 2.43 nm in the left edge region, 1.07 nm at the center, and 2.05 nm in the right edge region. These results confirm the homogeneous thermal influence of the Sombrero profile across the entire lens surface.

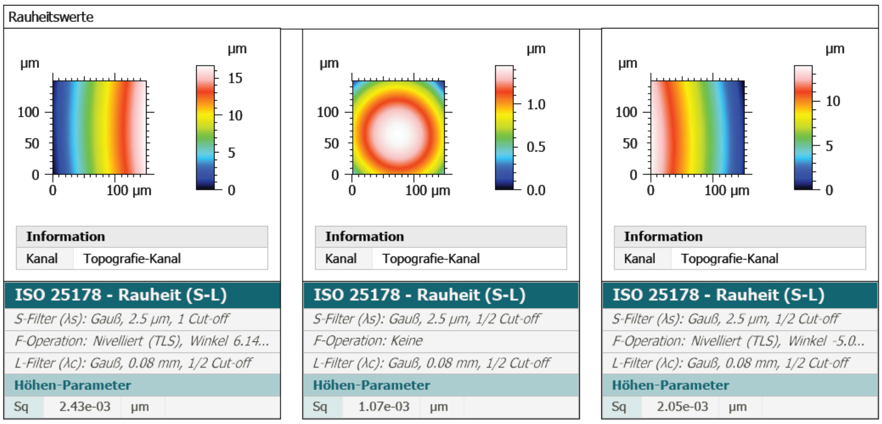

Fig. 5. Surface roughness maps of laser-polished mini-lens surfaces. (a) Left edge region, (b) center, (c) right edge region.

Form Deviation: Figure 6 shows the extracted cross-section of the lens surface in comparison to the ideal shape. The form deviation was reduced from prior values of approximately 2 µm to values around 1 µm. While general shape fidelity was significantly improved, a periodic waviness pattern remained. This structure is attributed to the stitching fields of the upstream SLE process, which introduce a baseline deviation that cannot be fully eliminated through thermal polishing alone.

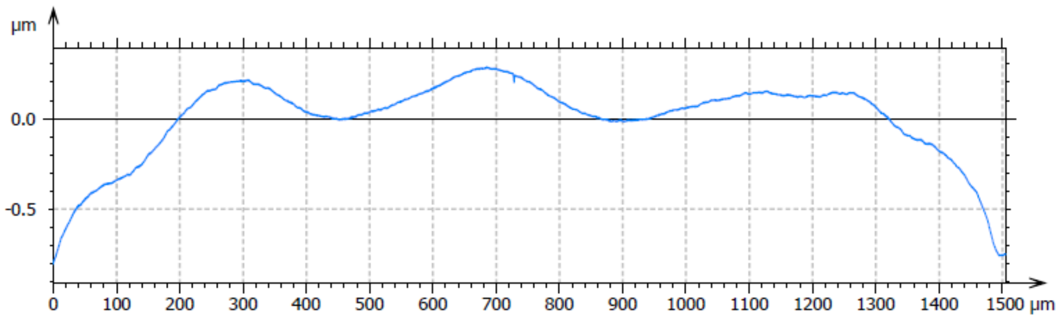

Fig. 6. Form deviation (measured shape – target geometry). Residual waviness results from the stitching pattern introduced by the SLE process.

The combination of quasi-stationary energy input and enhanced thermal homogeneity enabled by the Quasi-Beamforming strategy leads to a significant improvement in polishing quality. Surface roughness is notably reduced, particularly in the edge region of the lens, where previous approaches struggled to achieve uniform results. Form deviation is also decreased, resulting in better conformity to the intended lens geometry. In addition, the reduced exposure time lowers the overall thermal stress on the component, thereby minimizing the risk of microcracking or deformation. Compared to fixed beam-shaping methods such as DOEs, the dynamic nature of the Quasi-Beamforming approach provides greater flexibility and robustness, making it especially suitable for scalable wafer-level manufacturing of miniaturized optical components.

4. Conclusion

The Quasi-Beamforming laser polishing strategy represents a significant advancement in the fabrication of miniaturized optics. By shaping the thermal input using a dynamic Sombrero-profile via galvanometric scanning, this method addresses the key limitation of previous techniques: insufficient polishing in the edge region. The improved surface roughness of 2.5 nm RMS and reduced form deviation of 1 µm underline the effectiveness of this approach. This strategy opens new possibilities for scalable, high-quality, and cost-effective production of complex optical elements.

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