Photochemical welding of silica optical components to silicone rubber by F$_2$ laser

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Abstract. Photochemical welding of fused silica glass to silicone rubber has been demonstrated by 157-nm F$_2$ laser-induced photochemical modification of the silicone surface in contact with the glass. Fused-silica coverslips (150 $\mu$m thick), silica optical fibres (125 $\mu$m diameter), and 2.9-$\mu$m diameter microspheres were successfully welded onto 2-mm-thick silicone rubber by irradiating the silicone surface through the partially transparent glasses. Sufficient photochemical conversion for strong welding was provided by multiple exposures of tens to thousands of pulses in a narrow optimized fluence window near ~6-mJ/cm$^2$ per pulse.

1. Introduction

As mechanical systems become smaller, laser microwelding is emerging as the most promising approach to provide micron-scale heat sources with minimized heat-affected zones. [1,2] However, thermal transport together with the flow of the melt phase poses challenges on further downsizing of such micro-devices, particularly in metals. On-the-other-hand, non-thermal processes such as photochemical surface modification are alternative directions in laser micro-joining that are attractive for transparent glasses and polymers to provide biological or optical functions in micro-Total Analysis or lab-on-chip systems. [3-5]

In this paper, we build on our previous F$_2$-laser studies [6,7] of silicone rubber [(SiO(CH$_3$)$_2$)$_n$] to demonstrate the photochemical welding of silica optical components onto silicone rubber surfaces. In this approach, micro-optical components with high transparency at the 157-nm laser wavelength were photochemically welded onto a flexible silicone substrate without driving thermal effects such as melting, pyrolysis, or heat-affected damage. Such facile means for bonding optical components is highly attractive to simplify packaging and improve the robustness of optical systems in comparison to the rigid and delicate components presently used in optical telecommunication, biophotonic, and sensor applications. In our previous work, F$_2$-laser irradiation of silicone rubber led to surface swells, which were shown to consist of carbon-free silica glass. [8,9] F$_2$-laser photodissociation of silicone molecules together with the generation of active atomic oxygen O(1D) from molecular oxygen were essential components in this photochemical modification, defining a new means for creating flexible optical circuits comprising of glass films and rib waveguides on silicone substrates.

In the present work, silica optical components consisting of a thin plate, a Telecom optical fiber and glass microspheres were photochemically welded to silicone rubber surfaces by F$_2$-laser exposure.
Optimal laser exposure conditions are presented that provides strong bonding. We further show the selective welding of silica microspheres can form line arrays and other patterns by using masks to shape the laser beam on the silicone surface during welding.

2. Laser Exposure
The fused silica optical components to be photchemically welded were a 150-µm-thick fused silica plate, a Telecom silica optical fiber of 125-µm diameter (SMF-28) and silica microspheres of 2.9-µm diameter (Admatechs, SC8200-SQ). Each silica component was made to physically contact a 2-mm-thick silicone rubber substrate. The silicone-glass interface was exposed to F2 laser (Lambda Physik, LPF220) radiation through the fused silica, which had 157-nm absorption of 10 - 20 cm⁻¹. The optical beam path was flushed with high purity nitrogen gas to eliminate strong 157-nm absorption by ambient oxygen. The laser pulse duration was ~15 ns. The single pulse laser fluence was varied at the silica surface from ~3 to ~10 mJ/cm² by rotating dielectric mirrors in the beam path. A cursory investigation of higher fluences up to the ablation threshold [6] of 140 mJ/cm² was also made. The effect of pulse number on welding strength was examined carefully in the range of 3 to 3,000 pulses, with higher exposures to 90,000 also applied in several cases. Based on experience in optimizing the formation silica waveguides, the pulse repetition rate was fixed at 10 Hz. [8,9] All exposures were made at room temperature.

3. Results and discussion
Figure 1 shows a fused silica plate (10 x 5 mm²) welded onto silicone rubber (10 x 5 mm²) after F2 laser irradiation with ~6-mJ/cm² single pulse fluence and 3,000 pulses. A tug of the welded sample did not induce separation. Previous work has shown that 6-mJ/cm² fluence can drive photochemical modification of silicone into silica without damage [8,9]. Since the F2-laser ablation threshold for silicone is 23× higher at ~140 mJ/cm² [6], this bonding must be non-thermal and can only be due photochemical reactions. Laser fluence below 6 mJ/cm² could also weld silica to silicone rubber, but higher laser fluence offered shorter processing time. Application of 3,000 pulses at ~10-mJ/cm² fluence produced a non-welded area in the centre of the irradiated area that might arise from slight laser heating and thermal expansion breaking the contact between the silicone and the silica plate. Therefore, the 6-mJ/cm² laser fluence is preferable here for welding the whole thin fused silica plate.

The result of photochemical welding of a 125-µm-diameter silica optical fibre to silicone rubber is shown in figure 2. Here, a similar laser exposure of 3,000 pulses at ~6-mJ/cm² single pulse fluence was applied. However, focussing by the cylindrical fibre increased this exposure to ~20 mJ/cm² at the silicone surface. A lower exposure of 1,200 pulses at ~6-mJ/cm² fluence (at glass surface) also led to welding, but the fibre could be easily pulled apart from the silicone. Figure 3 shows an optical microscope image of the silicone surface after pulling apart a fibre welded with 1,200 pulses. One can see the physical removal of the modified silicone-glass in the narrow 20-µm contact region with the

![Figure 1. Photograph of a photochemically welded fused-silica plate (10 x 5 mm²) on silicone rubber (10 x 5 mm²).](image1)

![Figure 2. Photograph of a photochemically welded silica optical fibre on silicone rubber.](image2)
fibre. This 20-µm wide trench also coincides with the illumination area of the F2 laser beam after being focused by the cylindrical fibre. Such focussing to the contact area is attractive in efficiently using the available F2-laser light. Moreover, no melting phase is apparent on the welded silicone surface, as seen in figure 3.

Figure 3. Microscope image of silicone rubber surface after removal of a welded silica optical fibre.

Figure 4. Side view microscope images of silica optical fibres on silicone rubber before (a) and after (b) F2-laser irradiation of the fibre on the right side. Note a ~8-µm rise of the welded fibre.

The side views of the silica optical fibre on silicone rubber were photographed before and after F2 laser irradiation as shown in figure 4. Due to surface swelling during the photochemical modification of the silicone rubber, the silica optical fibre inside the irradiated area (right side) is ~8 µm higher than the uniradiated fibre (left side) as shown in figure 4(b). Here, the laser exposure was 3,000 pulses at ~6-mJ/cm² single-pulse fluence. For laser assembly and packaging of micro-optical components, such swelling effects must be accounted to ensure low insertion loss coupling between various welded optical components. This is as shown in figure 5. Here, the laser exposure was 90,000 pulses of the F2 laser at ~10-mJ/cm² fluence per pulse. [8,9] The silica optical fibre was positioned under the optical microscope to align with one waveguide and then laser-welded in position. Although vertical misaligned of the waveguides did not provide optical coupling here, improvements in alignment may make this laser approach feasible for both fabrication and packaging of micro-optical circuits on flexible silicone substrates.

For welding silica microspheres, samples were prepared by dispersing microspheres in methanol onto the silicone rubber, and then air-blown to remove excess spheres. A single layer of the microspheres resulted as shown in figure 6(a). Note a large variance in microsphere diameter. To selectively weld microspheres into patterns on the silicone rubber surface, a F2-laser optical projection system described previously [10] was used to project a grating amplitude mask and produce 5-µm-wide illumination lines on the microsphere-coated silicone. Here, only 20 laser pulses at ~3 mJ/cm² fluence were sufficient to induce welding due to the strong focussing effect of the microsphere. After the F2-laser exposure, sticky tape was applied four times to remove the non-welded microspheres, leaving only the laser-exposed microspheres that are now patterned in parallel line arrays as shown figure 6(b). The welded microspheres are strongly confined to within the 5-µm-wide illumination lines, demonstrating the selective welding by laser patterning on the sample. A smaller exposure size of 2.5 µm width yielded even narrower lines of microspheres aligned on silicone rubber as shown in figure 6(c). The present pseudo-random arrangement of microspheres was limited by the large diameter dispersion on first assembly (figure 6a), and can be improved with better quality sources of...
microspheres to eventually generate straight line arrays of microspheres for developing novel resonant optical waveguides [11].

![Figure 5](image1.png)

**Figure 5.** Microscope image of a silica optical fibre welded to silicone rubber for the purpose of coupling light to rib waveguides (left), formed by F$_2$-laser photochemical modification of the silicone surface waveguides.

![Figure 6](image2.png)

**Figure 6.** Microscope images of fused silica microspheres of ~2.9 μm in diameter on silicone rubber: before F$_2$-laser exposure (a), after F$_2$-laser exposure with 5-μm-wide lines (b) and with 2.5-μm-wide lines (c).

4. Conclusions

Photochemical welding of a fused silica glass to a silicone rubber was demonstrated by 157-nm F$_2$ laser irradiation. The bonding process was attributed to photochemical modification of silicone to silica, and chemical bonding to the contacting glass. Thin silica plates, optical fibers, and silica microspheres were strongly bonded to silicone with faint F$_2$ laser light of ~6-mJ/cm$^2$ fluence applied over several tens to thousands of laser pulses. By patterning of the laser beam, laser welding could be directed at selected microspheres to define patterned arrays or gratings of microspheres. These demonstrations suggest new approaches for fabricating, assembling, and packaging of micro-optical components for optical circuit and sensor applications requiring flexible substrates.

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