Photochemical writing of silica optical waveguides in silicone rubber by F$_2$ laser

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Abstract. Photochemical writing of silica (SiO$_2$) optical waveguides in silicone [(SiO(CH$_3$)$_2$)$_n$] rubber has been successfully demonstrated by 157-nm F$_2$ laser-induced photochemical modification of silicone into silica. The 2-mm-thick or ~40-μm-thick silicone rubber was exposed to F$_2$ laser through a thin (~0.2 mm) air layer. A proximity Cr-on-CaF$_2$ photomask with 8- to 16-μm-wide slits controlled the exposure size to define the width of the silica waveguides. A laser processing window to generate crack-free waveguides with good optical transparency was found by varying the number laser pulse, pulse repetition rate and single pulse laser fluence. Otherwise, rapid or excess exposure of the F$_2$ laser caused cracking of the silica waveguides. The waveguides were found to guide both red (635-nm) and infrared (1550-nm) wavelength light with propagation loss estimated to be ~15 and ~6 dB/cm, respectively. Most of the loss originates in Rayleigh scattering from numerous inclusions originally present in the commercial 2-mm-thick silicone rubber.

1. Introduction

In laser processing, the 157-nm wavelength of the F$_2$ laser is the shortest commercially available [1] with advantages of driving strong absorption in transparent materials, including the best UV-grade fused silica (SiO$_2$) [2,3]. In this case, crack-free excisions with near-optical flat surface figure can be ablated in silica surfaces because of strong interactions and a low etching rate. The high photon energy (7.9 eV) of the F$_2$ laser can also induced refractive index changes in silica to fabricate buried optical waveguides [4]. This is an alternative to modification with near-IR femtosecond (fs) lasers which are widely applied in microfabrication [5] to take advantage of small heat-affected zones for machining metals and polymers [6,7] or inducing refractive index changes internally in glasses to form buried optical waveguides by multi-photon processes [8,9].

We have been applied the F$_2$ laser to induce photochemical reactions in silicone [(SiO(CH$_3$)$_2$)$_n$] for various microfabrication purposes [10,11]. When the F$_2$ laser irradiates silicone, the surface is photochemically modified into carbon-free silica, accompanied by swelling of the exposed area. Based on this photochemical modification, silica rib optical waveguides have been formed on the silicone for the purpose of fabricating micro-optical components or optical circuits on flexible substrates [12].

In this paper, we expand on this previous work to better delineate the laser processing windows for generating crack-free silica waveguides to guide both red (635-nm) and infrared (1550-nm)
wavelength light. Scanning electron microscopy (SEM) of the silica ribs is reported and the underlying causes of silica cracking are assessed. We clarify that the optimum laser processing conditions for generating symmetric waveguide modes that couple well to standard single mode Telecom fiber and offer modestly low propagation loss.

2. Experimental
An F2 laser (Lambda Physik, LPF220) of ~8 x 25 mm² beam size irradiated the silicone rubber surface through a Cr-on-CaF₂ proximity photomask containing 8- to 16-μm wide slits. The photomask was positioned ~0.2 mm from the silicone surface in air to provide the oxygen that was essential for the photochemical modification of silicone. The laser pulse duration was ~15 ns. Without focusing optics, the laser fluence leaving the photomask could be varied from ~2.5 to 10 mJ/cm² with an optical attenuator. Higher fluence was available with a CaF₂ cylindrical focusing lens. The laser repetition rate and pulse number were changed from 10 to 100 Hz and from 1,600 to 180,000, respectively. The silica ribs were formed on the silicone rubber at room temperature. For comparison, waveguides were formed on a 2-mm thick commercial silicone sheet and a ~40-μm thick silicone layer (Quantum Silicone, QSIL216) spun onto a silica glass substrate.

3. Results and discussion
In order to find the laser processing window to generate crack-free waveguides, the conditions of number of laser pulses, pulse repetition rate and laser fluence were widely varied. Figure 1 shows the demarcation between crack-free and cracked silica formed under various laser pulse number and pulse repetition rates. The single pulse laser fluence was ~10 mJ/cm² for each data point. Crack-free silica was formed over a wide range of total laser pulse numbers of 1,600 to 72,000 when a repetition rate of 10 Hz was applied. At the 72,000-pulses, the silica ribs fabricated at 10 and 20 Hz were crack-free.

Figure 2 shows the dependence of the silica rib height on pulse repetition rate. The laser pulse number was 72,000 for each sample. The silica ribs swelled to between ~6.4 and ~7.0 μm height, except in the case of 100 Hz, which yielded a significantly larger silica rib height of ~8.8 μm. This anomalous swelling for 100-Hz repetition rate likely arises from a thermal incubation effect. Because exposures at 30 Hz or higher generated microcracks, only lower repetition rates were used to form the silica rib waveguides below.

The silica rib height was also characterized as a function of number of laser pulses as shown in figure 3. The silica rib height increased from ~0.3 to ~6.6 μm over this increasing exposure range for single pulse fluence of ~10 mJ/cm². A larger 90,000-pulse exposure created a somewhat larger silica rib height of ~7.0 μm (versus ~6.6 μm for 72,000 pulses) but also defined the upper exposure limit for
forming cracks at 10 Hz repetition rate. The silica ribs fabricated at 2.5-mJ/cm² fluence and at 90,000-pulses were also cracked, though the rib height was clearly smaller (~4.5 μm) at this lower fluence. This suggests that pulse number is a more important control parameter than laser fluence for defining the microcracking onset in F₂-laser formed silica ribs. However, figure 3 shows that laser pulse number is a useful control parameter for defining silica rib height. To maximize the volume of silica generated while minimizing the exposure time, a processing window of 30,000 to 72,000 pulses at ~10 mJ/cm² fluence and 10 to 20 Hz repetition rate is recommended, yielding ~6-μm high glass ribs that are free of cracks. Higher single-pulse fluence will damage the substrate. [12]

![Figure 3](image3.png)

**Figure 3.** Dependence of silica rib height on the number laser pulse for ~2.5- and ~10-mJ/cm² single pulse laser fluences.

Figure 4 presents the SEM (Hitachi S-4500) image of an optimized silica rib waveguide, formed with 9,000 pulses at 10-mJ/cm² fluence and 10-Hz repetition rate [12]. The ~15-μm wide line (FWHM) exceeds the 8-μm wide laser exposure line due to diffraction by the slit and scattering by the silicone. A ~15-nm surface roughness was measured by AFM at the top surface of a silica waveguide. This compares favorably with a measured ~5 nm roughness for the non-radiated silicone surface and suggested that optical losses due to surface roughness scattering will not be overly large.

![Figure 4](image4.png)

**Figure 4.** SEM image of the silica rib fabricated on silicone rubber.

The propagation loss of the 6-μm high waveguides was estimated by an exponentially representation of light propagating in the waveguide and scattered by the rib surface. Figure 6 shows a CCD image of scattered 1550-nm light and the exponential representation for a 6 dB/cm loss. The propagation loss at 635 nm was ~15 dB/cm. The significant factor in the loss was scattering and absorption of the evanescent field in the silicone substrate. Substantial losses of 38 dB/cm at 633 nm and 10.5 dB/cm at 1550 nm were measured in the unmodified silicone, which is attributed to Rayleigh scattering from numerous inclusions. In contrast, waveguides formed the much clearer spin-coated silicone rubber (~40-μm thickness) yielded much improved losses of <1.5 dB/cm at 1550 nm.

4. Conclusions
Silica optical waveguides were fabricated on silicone rubber by F₂ laser-induced photochemical reactions. A laser processing window was defined to generate crack-free waveguides with good transparency. The best waveguides were formed with 10-mJ/cm² fluence, 20-Hz repetition rate and ~72,000-laser pulses. Rapid or excess exposure of the F₂ laser caused cracking of the silica waveguides. The waveguides on 2-mm substrates guided both red and infrared wavelengths with propagation loss.
of ~15 and ~6 dB/cm at 635- and 1550-nm wavelengths, respectively, but improved to <1.5 dB/cm loss at 1550 nm for the ~40-μm-thick spin-coated silicone film. The guiding mode profiles are sufficiently small for coupling to standard single-mode optical fibers. The results demonstrate a new opportunity for fabricating micro-optical components and optical circuits on flexible substrates.

**Figure 5.** CCD near-field images of the guiding mode profile of red (635-nm) (a) and infrared (1550-nm) (b) light.

**Figure 6.** Propagation loss measurement of the silica waveguide at 1550 nm wavelength; a top view image (a) and dependence of scattering loss on the distance (b).

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