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Optical loss measurements in femtosecond laser written waveguides in glass

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Abstract

The optical loss is an important parameter for waveguides used in integrated optics. We measured the optical loss in waveguides written in silicate glass slides with high repetition-rate (MHz) femtosecond laser pulses. The average transmission loss of straight waveguides is about 0.3 dB/mm at a wavelength of 633 nm and 0.05 dB/mm at a wavelength of 1.55 μm. The loss is not polarization dependent and the waveguides allow a minimum bending radius of 36 mm without additional loss. The average numerical aperture of the waveguides is 0.065 at a wavelength of 633 nm and 0.045 at a wavelength of 1.55 μm. In straight waveguides more than 90% of the transmission loss is due to scattering.
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Optical breakdown of femtosecond laser pulses inside transparent materials is a topic of high current interest [1–4]. One interesting effect of the interaction of tightly focused femtosecond laser radiation with transparent materials is the modification of the refractive index of the exposed area. Although many questions remain about the details of the mechanism for the index change, numerous studies have investigated waveguide fabrication inside transparent materials such as silicate glasses [5–13]. The unique advantage of utilizing tightly focused femtosecond pulses is that the waveguide can be fabricated in three-dimensions inside the material without damaging the material surface [5–12]. Indeed, simple photonic devices such as waveguide couplers, beam shapers, amplifiers, interferometers and resonators have already been demonstrated [9–12, 14–17]. However, one of the most important characteristics for practical applications of these waveguides, their optical loss, has received little attention [18–20]. In this paper, we report the results of transmission loss measurements of both straight and curved waveguides written in silicate glass using femtosecond laser pulses. We also determine the effective numerical aperture (NA) and scattering loss of these waveguides.

To fabricate waveguides we use a Ti:sapphire oscillator with a central wavelength of 800 nm, a repetition rate of 25 MHz, an on-target pulse energy of 7 nJ, and a pulse duration of about 60 fs. The waveguides are fabricated in $75 \times 25 \times 1.0\ mm^3$ silicate glass slides (Corning 0215). The laser pulses are focused inside the sample by a 1.4-NA oil-immersion microscope objective, and the slide is translated perpendicularly to the incident direction of the laser beam. Because of the high repetition-rate of the laser oscillator, successive laser pulses arrive at the sample at a rate faster than the thermal diffusion rate in the glass [21]. Therefore, as energy is deposited through nonlinear absorption at the focal point, a volume around the focus is heated to the melting point. After the exposed area is translated out of the focus, the material resolidifies nonuniformly producing an index change. Continuous translation of the sample results in a uniform, embedded waveguide, with core diameters inversely proportional to the writing speed [4,11]. The waveguides reported in this paper were written along the length of the slide with writing speeds ranging from 1 to 20 mm/s. The waveguides have diameters ranging from 9.0

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to 10.5 μm, depending on the translation speed. In order to guarantee no interaction between waveguides, we spaced the waveguides by more than 100 μm from each other.

A schematic diagram of the loss measurement setup is shown in Fig. 1. A continuous wave laser beam from a linearly polarized single-mode He–Ne laser (633-nm wavelength) or 1.55-μm laser diode is expanded by 10× telescope T. Iris I1 is used to control the beam diameter and hence the NA of the beam incident on the waveguide. A beam-splitter directs half the beam onto photo-detector D1 used to monitor the input energy. The laser beam is focused onto the input surface of the waveguide using a 0.25-NA (10×) microscope objective, and a CCD camera is used to monitor the input coupling. The output of the waveguide is collected by an objective and measured by detector D2. Output iris I2 prevents scattered transmitted light from reaching the detector. Incoherent light from a lamp illuminates the input surface of the waveguide to ensure that the input laser beam is focused exactly on the waveguide. The CCD image allows us to optimize the coupling of light into the waveguide before each measurement. Detector D1 measures the input power of the waveguide after calibrating the transfer efficiency of the beam splitter, the input objective, and the Fresnel reflection on the input surface. Detector D2 measures the output power through the waveguide after calibrating the transfer efficiency of the output objective, beam splitter, and the Fresnel reflection on the output surface of the waveguide.

To determine the transmission losses we cut the glass slides in half, polished the end faces, and then measured the intensity of the transmitted signal through the shortened waveguide. The transmission loss is determined from the ratio of the transmission of the original waveguide to that of the shortened waveguide. Fig. 2 shows the transmission loss of waveguides fabricated at various translation speeds measured with an incident NA of 0.03. Each datapoint is the average of about twenty measurements. In the visible at a wavelength of 633 nm, the average loss is about 0.3 dB/mm; the minimum loss is 0.16 dB/mm. In the infrared the loss is much lower: at a wavelength of 1.55 μm the average loss is 0.05 dB/mm and the minimum loss 0.029 dB/mm. The higher loss at 633 nm can be attributed to the greater sensitivity of shorter wavelengths to inhomogenities of the waveguide, such as sidewall roughness. The optical loss of the waveguides is acceptable for applications in integrated optical circuits which require wave guiding over relatively short lengths (e.g., several millimeters).

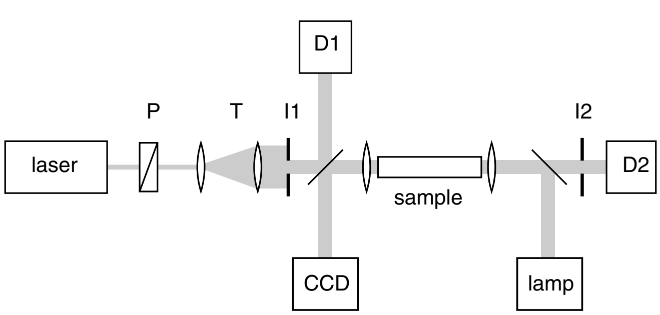

Fig. 1. Loss measurement setup for optical waveguides written in glass by femtosecond laser pulses. P = polarizer; T = telescope, I1,2 = iris, D1,2 = detector; CCD = charged-coupled device camera.

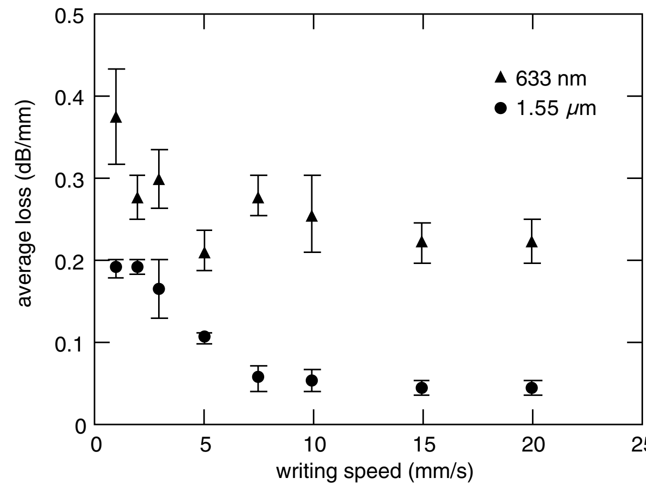

Fig. 2. Translation speed dependence of the optical loss at 633 nm (triangles) and 1.55 μm (circles). Error bars show variance among 10 waveguides written at the same speed.

Because the waveguides result from the melting and resolidification of the glass around a spherical focus they have a circular cross-section and should be polarization-insensitive. We measured the polarization-dependence of the transmission losses by using a linear polarizer and a half-wave plate before the input objective and measuring the output of the waveguide. The maximum loss difference for two different linear polarizations in waveguides fabricated at 5 mm/s is only 0.003 dB/mm at 633 nm, confirming the polarization-independence of the waveguides.

To determine the NA of the waveguides, we measured the dependence of the transmission loss on the NA of the input beam by changing the aperture of iris I1. By underfilling the microscope objective used to couple the light into the waveguide, the effective NA is reduced. If the NA of the input beam is larger than the NA of the waveguide, less light is coupled into the waveguide and so the loss should increase. Fig. 3 shows the NA dependence for waveguides fabricated at a speed of 20 mm/s. The loss increases once the NA of the input beam exceeds 0.04 (at 1.55 μm) and 0.065 (at 633 nm). The NAs of waveguides fabricated with lower speeds range from about 0.055 to 0.075 (at 633 nm) and 0.03 to 0.06 (at 1.55 μm).

From the NA measurement, we can determine the modes that the waveguides can support from the normalized waveguide parameter [22]

$$V = \pi d(\mathrm{NA})/\lambda_0, \tag{1}$$

where d is the diameter of the waveguide, and λ_0 is the vacuum wavelength. For a waveguide fabricated with a writing speed of 20 mm/s, the diameter of waveguide measured

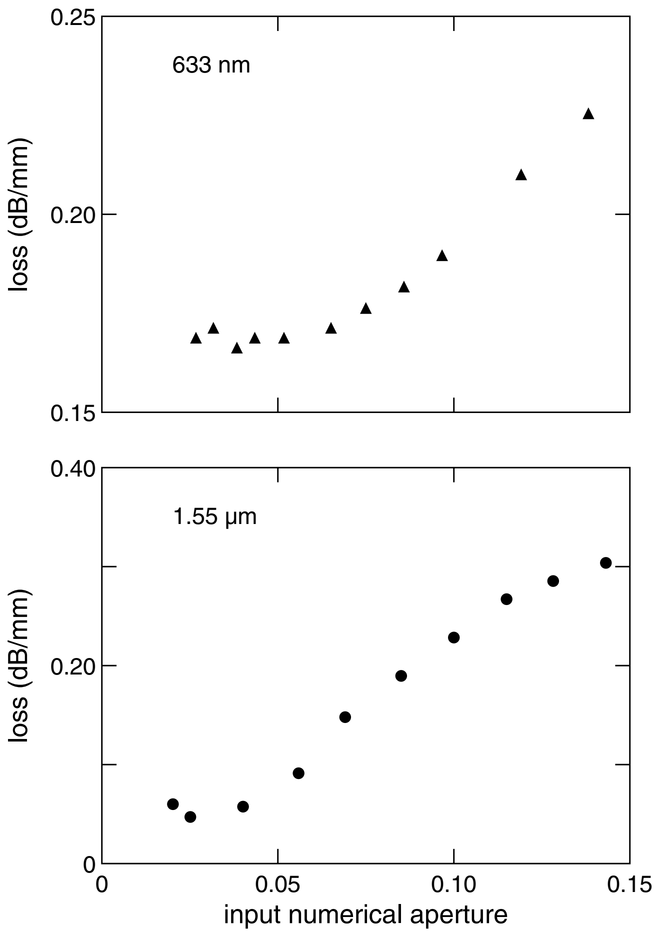

Fig. 3. Dependence of the coupling loss on numerical aperture of the input beam at 633 nm (top) and 1.55 μm (bottom).

from optical microscopy is 10 μm, the NA at 633 nm is 0.065, which gives $V = 3.23$ according to Eq. (1). The single mode condition is $V < 2.405$, indicating that the waveguide is multimode at this wavelength. Imaging the near-field pattern on a CCD shows a LP_{11} mode (Fig. 4(a)), confirming multimode operation. At 1.55-μm wavelength, the normalized waveguide parameter V is 1.32, and the near-field pattern is single mode (Fig. 4(b)).

The measured NA allows us to estimate the index change (Δn) of the waveguides. Assuming a square index profile, $\mathrm{NA} = \sqrt{n_1^2 - n_2^2}$, where n_1 is the index of the waveguide, and n_2 is the index of the substrate glass [22]. For Corning 0215, $n_2 = 1.52$. For a waveguide of NA = 0.065, the index change Δn is about 1.4×10^{-3}, which is of the same order as those previously reported in similar materials [9,12].

We also measured the bending losses of curved waveguides fabricated by mounting the glass substrate on a rotating stage. The resulting waveguides were obtained at translation speeds ranging from 3.5 to 7.5 mm/s; the angle subtended by the curved waveguides is larger than 45°. Fig. 5 shows the bending losses at 633 nm for waveguides with different bending radii. For bending radii larger than 40 mm, the loss is independent of the radius showing that at those radii, the loss caused by the bending is negligible. The bending losses increase rapidly, however, as the bending radius is decreased below 36 mm.

To establish the source of the losses we measured the scattering loss through of the waveguides by replacing the detector in the setup shown in Fig. 1 with a 60-mm diameter integrating sphere, as illustrated in Fig. 6. To maximize the coupling of light into the waveguide we fixed the NA of the input beam at 0.03. Because of the low NA of the input beam and high index difference between the polished glass substrate and the air, the slide acts as a slab waveguide for any light that is scattered from the embedded waveguide. Nearly all the scattered light therefore exits from the far end of the substrate slide. With the observing window covered with scattering material, we compared the detector signal when 633-nm light is coupled into a waveguide to the signal when light is moved off the waveguide. The ratio of these values gives an upper bound for the additional loss caused by absorption in the waveguide (on top of the glass matrix absorption). For straight waveguides fabricated at writing speeds of 20, 10 and 5 mm/s these

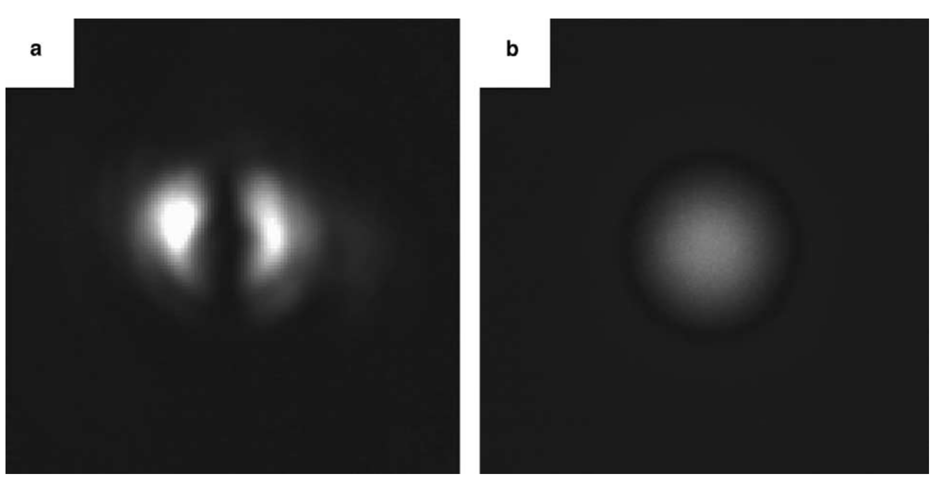

Fig. 4. Near-field output of a waveguide fabricated at 20 mm/s. (a) LP_{11} mode at 633-nm wavelength and (b) LP_{01} mode at 1.55-μm wavelength.

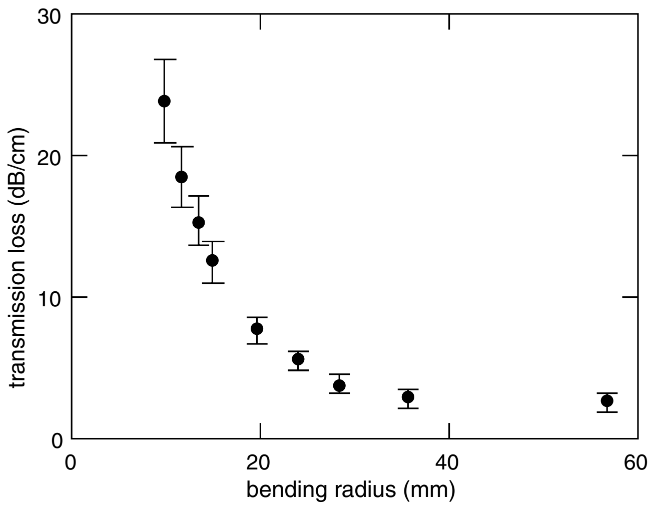

Fig. 5. Bending losses of waveguides with different bending radii for an input wavelength of 633 nm.

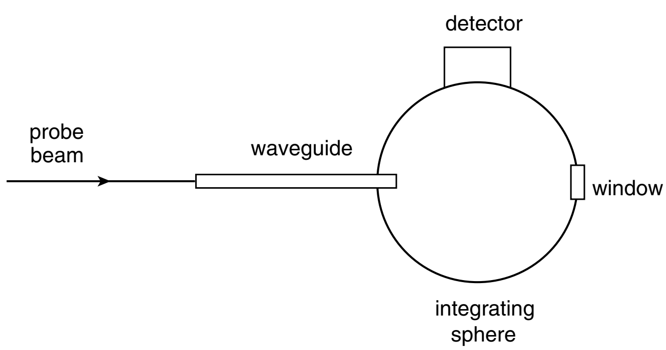

Fig. 6. Scattering loss setup. The observation window was covered with a scattering disk in order to collect all the light coupled into the waveguide.

ratios are 95%, 96% and 91%, respectively. The transmission losses of these waveguides must therefore mainly be due to scattering. Although the waveguides look smooth under optical microscopy (Fig. 7), this scattering may arise from sub-micrometer roughness of the sidewalls caused by vibration during translation of the sample.

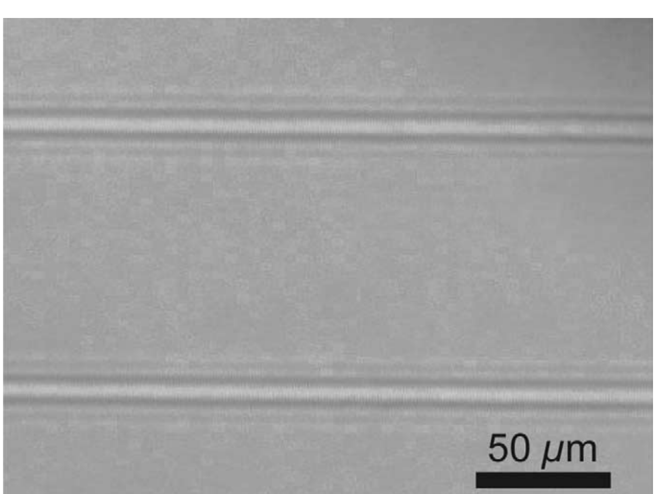

Fig. 7. Top view microscope image of a typical waveguide.

In conclusion, we determined the losses of straight and curved femtosecond laser-micromachined waveguides in silicate glass slides. The average loss of straight waveguides is about 0.3 dB/mm at a wavelength of 633 nm and 0.05 dB/mm at 1.55 μm. The polarization-dependence of the loss is minimal and the bending loss at 633 nm wavelength is negligible for bending radii larger than 36 mm. The average NA of straight waveguides is about 0.065 at 633 nm and 0.045 at 1.55 μm, corresponding to an index change on the order of 1.4×10^{-3}. Our results also show that in straight waveguides, more than 90% of the total loss is due to scattering. Optimizing fabrication conditions, especially the stability of the translation stage, may further improve optical properties of these waveguides.

Acknowledgements

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