Low-loss broadband optical waveguides fabricated in glass by femtosecond laser direct writing

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ABSTRACT

The fabrication of optical waveguides with femtosecond laser direct writing is reported in two materials, Suprasil1 and Eagle2000. The influence of typical fabrication parameters, such as pulse energy and scan velocity, on the waveguide's spectral characteristics is explored from 500 to 1700 nm. Tests conducted in Suprasil1 evidence a strong presence of Rayleigh scattering, hindering the production of low-loss waveguides at short wavelengths. On the other hand, optical waveguides fabricated in Eagle2000 exhibited lower insertion losses at short wavelengths, enabling the fabrication of low-loss broadband optical waveguides with a two order of magnitude higher scan velocity when compared with Suprasil1.

Keywords: Femtosecond laser direct writing, integrated optics, low-loss broadband optical waveguides, Rayleigh scattering, Mie scattering

1. INTRODUCTION

Optical circuits are traditionally fabricated by photolithographic techniques, due to the technique's technological maturity. However, a recent approach uses a femtosecond laser to write the guiding core directly in the material [1]. Unlike photolithography, this technique offers prototyping flexibility, without the need for masks or multiple fabrication steps, and three-dimensional geometries, which are not feasible using traditional fabrication methods. Several materials are available, such as glasses, crystals, and polymers [2], with many integrated optical devices having been reported, including Bragg grating waveguides [3], power splitters [4, 5, 6], three-dimensional fan-out devices for multicore fiber coupling applications [7], integrated lasers [8], add-drop multiplexers [9], arrayed waveguide gratings [10], among others. Despite the possibilities, the spectral characteristics of the optical waveguides employed in such devices are far from ideal. Most of the studies present in the literature discuss waveguide loss at the 1550 nm region and, although infrared wavelengths are the most relevant for optical communications, shorter wavelengths are indeed important for applications like optical sensing relying on plasmonics or absorption measurements [11, 12]. Since shorter wavelengths are more affected by defects present in optical waveguides [13], understanding its loss mechanisms and their dependence with fabrication parameters is key to improve their quality as well as to maximize the performance of said devices.

In this work, we report a systematic study of the spectral behavior, from 500 to 1700 nm, of optical waveguides embedded in fused silica and alkaline earth boro-aluminosilicate glass using femtosecond laser direct writing, testing the influence of typical fabrication parameters, such as pulse energy and scan velocity, in insertion loss. The spectral characteristics of optical waveguides inscribed in both glasses are compared, with the suitability of both materials for the fabrication of low-loss broadband optical waveguides being discussed.

2. EXPERIMENTAL PROCEDURE

A fiber amplified femtosecond laser (Amplitude Systèmes Satsuma HP), with a second harmonic beam at 515 nm and a pulse duration of approximately 250 fs at 500 kHz, was used to induce the refractive index modifications. The linearly polarized beam was focused inside the Suprasil 1 and Eagle2000 substrates at a depth of 100 µm via a 0.55

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numerical aperture aspherical lens (New Focus 5722-A-H) mounted in a vertical piezo stage (PI P-725.4CD PIFOC). Optical waveguides were formed by transverse scanning the substrates in relation to the beam focus on Aerotech air-bearing linear stages (ABL10100-LN). Laser beam polarization was set parallel to the writing direction, and all waveguides were written on the same scanning direction to avoid the Quill effect [14].

To determine the spectral characteristics of the optical waveguides, the broad spectrum of a halogen lamp was coupled into a single-mode fiber (SMF-28) and butt-coupled to the entrance facet of the modification tracks. The substrates were mounted on an Elliot Martock MDE881 stage with piezo controls (Dali E-2100) and special holders for precise alignment of the input/output optical fibers. The light collected by a second butt-coupled optical fiber at the exit facet was inspected in an optical spectrum analyzer (ANDO AQ-6315B) from 500 nm to 1700 nm with a 10 nm resolution. All transmission spectra were normalized to the source spectrum to obtain the insertion loss. Index matching (Cargille series: AA $n_D^{25^\circ C} = 1.458 \pm 0.0002$) was used to minimize Fresnel reflections at both input/output fibers/facets. The side facets were also polished after writing in order to eliminate laser damage induced in the substrates' input and output facets, and to remove the waveguide tapered region created by the influence of the substrates' edge on the beam focus.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In this study, several sets of optical waveguides were inscribed in a fused silica (Suprasil 1) and alkaline earth boro-aluminosilicate glass (Eagle2000) with a varying pulse energy and scan velocity. The spectral characteristics of optical waveguides produced by femtosecond laser direct writing, as well as their dependence with the fabrication parameters, was analyzed from 500 nm to 1700 nm.

The insertion losses of 2.2 cm long optical waveguides inscribed in Suprasil 1, with a pulse energy ranging from 50 nJ to 400 nJ and a scan velocity of 100 µm/s (doubling after each waveguide) to 6400 µm/s, were measured, as depicted in figure 1. Here, an increase in insertion loss is visible whenever the wavelength decreases or increases from a certain position. It also depends on the fabrication parameters, presenting two distinct behaviors at shorter and longer wavelengths. Longer wavelengths display smaller insertion losses as pulse energy increases, increasing as

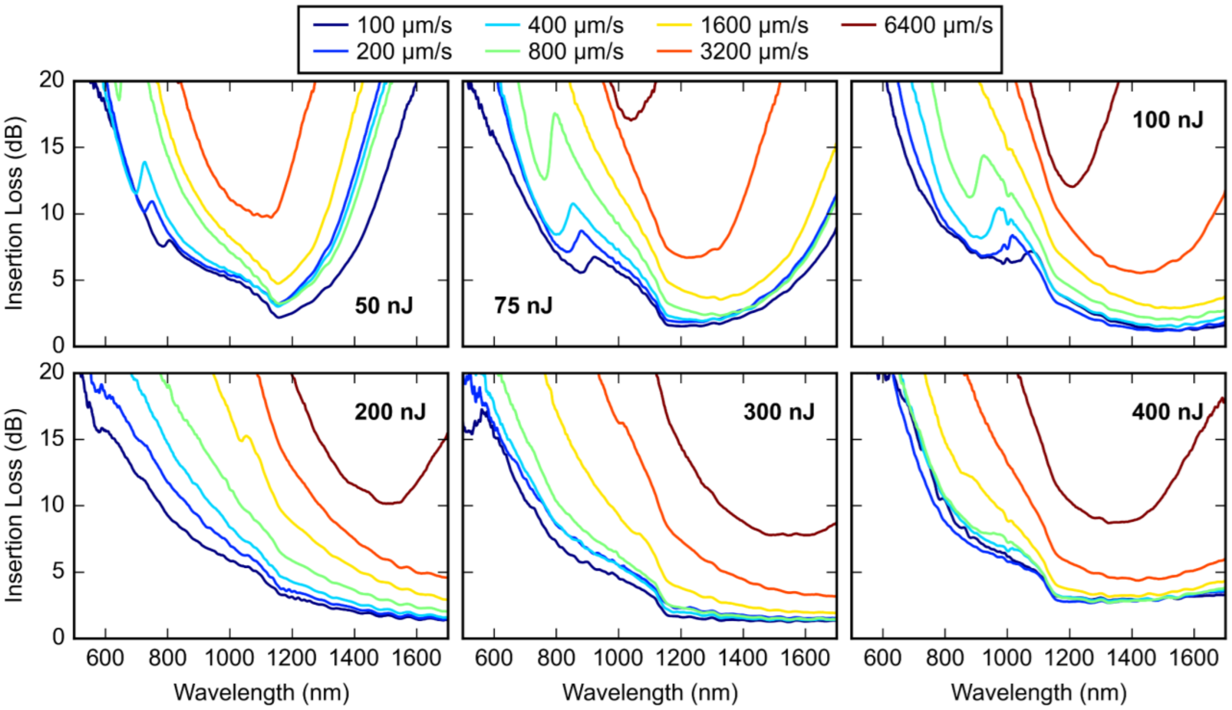

Figure 1. Insertion loss, as a function of wavelength, of 2.2 cm long optical waveguides inscribed in Suprasil 1. A pulse energy ranging from 50 to 400 nJ (at a repetition rate of 500 kHz) together with a scan velocity of 100 to 6400 µm/s was tested.

scan velocity increases. Shorter wavelengths also introduce increased insertion loss at higher scan velocities, with no clear dependence with pulse energy being found.

In a recent work [15], we showed that the longer wavelength dependent behavior originates from a monotonic growth in coupling losses as wavelength increases. This originates from the decrease in V-number, leading the guiding conditions closer to the cut-off condition and, therefore, increasing the mode field diameter, which translates into additional mode mismatch. We also concluded that, at longer wavelengths, coupling losses increase whenever the pulse energy is decreased and/or the scan velocity increased. This originates from the lower refractive index contrast achieved together with lower physical waveguide dimensions, deriving from a smaller net writing fluence, thereby increasing mode field diameter and, subsequently, mode mismatch. Regarding the short wavelength dependent behavior, it was seen to derive from a C/λ^4 trend in propagation loss. This trend was attributed to a strong Rayleigh scattering influence in propagation loss, which increased with scan velocity but presented no clear dependence with pulse energy. Despite Rayleigh scattering being the major contributor to propagation loss, an almost wavelength independent baseline loss was also identified, which was attributed to Mie scattering. An increase in the Mie scattering coefficient was seen as pulse energy increases, with its relationship with scan velocity not being clearly identified.

Despite the importance of fused silica in applications such as optofluidics [16] due to a simultaneous modification in refractive index, enabling the inscription of optical waveguides, and the existence of nanogratings [17], which allows the fabrication of embedded microfluidic channels [18], softer glasses present the possibility of creating optical circuits at roughly two orders of magnitude higher scan velocities, greatly decreasing fabrication times. As such, the

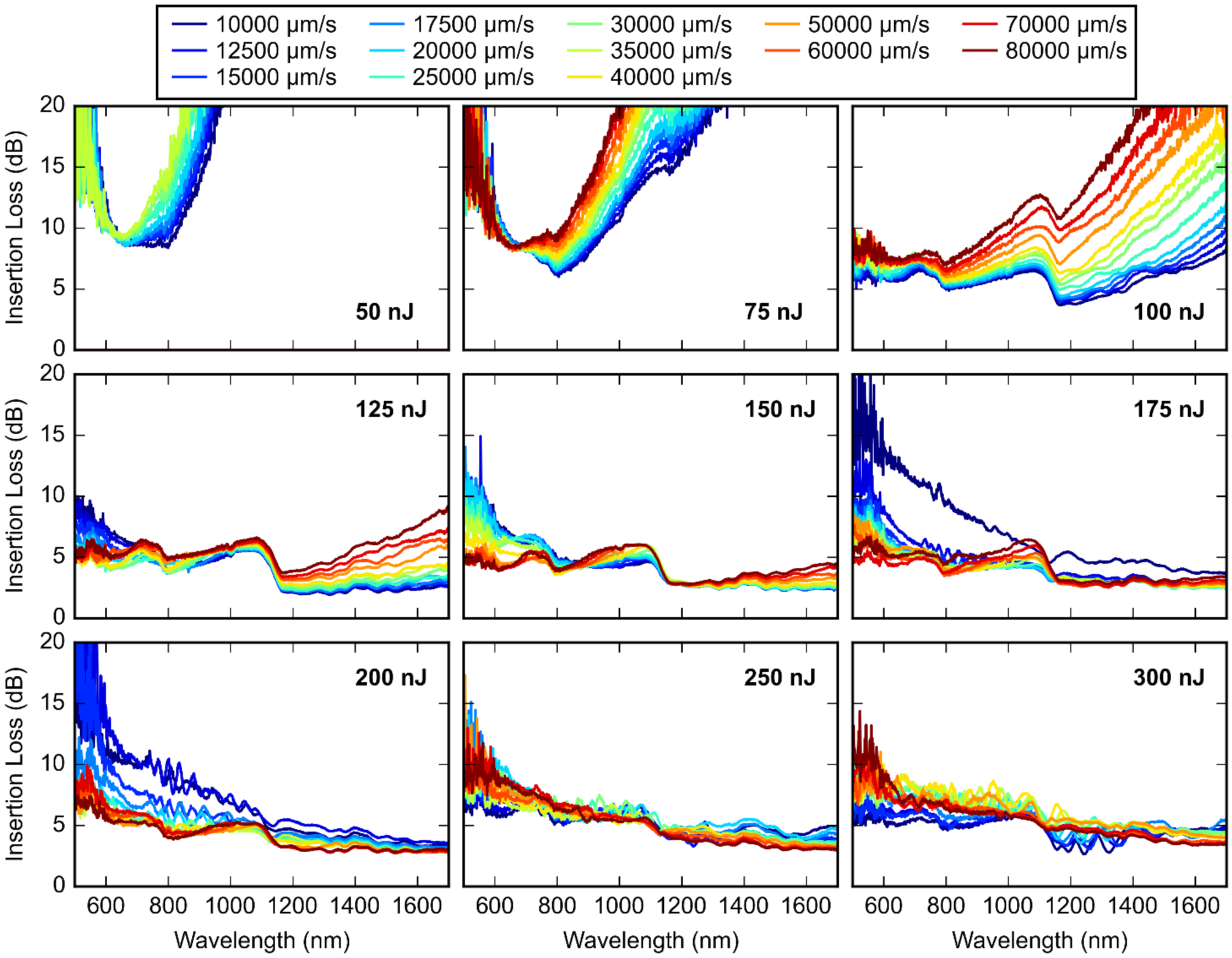

Figure 4. Insertion loss, as a function of wavelength, of 2.5 cm long optical waveguides inscribed in Eagle2000. A pulse energy ranging from 50 to 300 nJ (at a repetition rate of 1 MHz) together with a scan velocity of 10000 to 80000 µm/s was tested.

insertion losses of 2.5 cm long optical waveguides inscribed in Eagle2000, with a pulse energy ranging from 50 nJ to 300 nJ and a scan velocity of 10000 µm/s to 80000 µm/s, were also measured, as depicted in figure 2. Again, an increase in insertion loss is visible whenever the wavelength decreases or increases from a certain position. Like the optical waveguides fabricated in Suprasil 1, the spectral characteristics also depend on the fabrication parameters, presenting two distinct behaviors at shorter and longer wavelengths. Longer wavelengths still display smaller insertion losses as pulse energy increases, increasing as scan velocity increases. However, unlike in Suprasil 1, waveguides fabricated in Eagle2000 at higher pulse energy (in the range tested) present smaller insertion losses at shorter wavelengths. Scan velocity did not demonstrate a clear influence in insertion loss, with some cases showing lower losses at high scan velocity and vice versa.

When comparing the spectral characteristics of optical waveguides fabricated in Suprasil 1 and Eagle2000 one can observe the similarities. Although a more detailed study is required to discuss both coupling and propagation loss of optical waveguides in Eagle2000, some speculation about the processes behind them can be made through comparison with the study made in Suprasil 1 [15]. In contrast, one can argue that the process behind the behavior present at longer wavelengths in optical waveguides fabricated in Eagle2000 is identical to the one in Suprasil 1. In this range the loss should arise from coupling losses, since higher wavelengths as well as a smaller net writing fluence (created by lower pulse energies or higher scan velocities) reduce the optical waveguide's V-number. The insertion loss increase, at shorter wavelengths, of optical waveguides fabricated in Eagle2000 at lower pulse energies also indicate the existence of Rayleigh scattering, but the application of higher pulse energies greatly reduces its influence. Furthermore, when in comparison with optical waveguides in Suprasil 1, this Rayleigh scattering seems to be much less pronounced, enabling the fabrication of optical waveguides with optimal guiding characteristics over a very large wavelength range. The difference may originate in the modification process, since any imperfections created during the waveguide's inscription can be erased by the thermal accumulation present in Eagle2000.

There is no doubt that further work must be done in order to identify and quantify with certainty the processes behind the spectral behavior of optical waveguides fabricated in Eagle2000. Other fabrication variables, such as the writing laser's pulse front tilt, spatial beam profile, astigmatism, polarization state, pulse duration, repetition rate, and lens numerical aperture, should also be tested for future developments in the guiding characteristics of waveguides fabricated by femtosecond laser direct writing.

4. CONCLUSION

The guiding properties of optical waveguides fabricated by femtosecond laser direct writing in fused silica (Suprasil 1) and alkaline earth boro-aluminosilicate glass (Eagle2000) substrates were tested while varying processing parameters such as pulse energy and scan velocity. The insertion losses of such waveguides presented a mid-wavelength guiding band limited by increasingly higher losses at long and short wavelengths. By comparing the spectral characteristics of waveguides embedded in Eagle2000 with those in Suprasil 1, as well as knowledge obtained in this material in a previous work, we suspect that coupling losses most likely control the long wavelength behavior, with its monotonic growth, as wavelength increases, arising from an increasing mode mismatch. Additionally, coupling losses increased whenever the pulse energy decreased or the scan velocity increased, probably due to a less pronounced modification caused by a smaller net writing fluence. The insertion loss increase, at shorter wavelengths, of optical waveguides fabricated in Eagle2000 at lower pulse energies also indicate the existence of Rayleigh scattering, but the application of higher pulse energies greatly reduces its influence. Furthermore, when in comparison with optical waveguides in Suprasil 1, this Rayleigh scattering seems to be less pronounced, enabling the fabrication of low-loss broadband optical circuits with a two order of magnitude smaller inscription time.

Future work should be developed in order to identify and quantify with certainty the processes behind the spectral behavior of optical waveguides fabricated in Eagle2000. Improvement of the overall spectral characteristics of waveguides fabricated by femtosecond laser direct writing should be possible with further exploration of other fabrication parameters.

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