

Making smart phones smarter with photonics

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Abstract: Smart phones and tablets have become ubiquitous. Corning® Gorilla® Glass is well-known to provide durability and scratch-resistance to many smart phones and other mobile devices. Using femtosecond lasers, we report high quality photonic devices, such as a temperature sensor and an authentication security system, we believe for the first time. It was found that this kind of glass is an exceptional host for three dimensional waveguides. High quality multimode waveguides are demonstrated with the lowest measured loss value (0.027 dB/cm loss) to our knowledge in any glass using fs laser inscription. High quality (0.053 dB/cm loss) single-mode waveguides have been also fabricated using a fs laser scan speed of 300 mm/s, the fastest fabrication speed reported to date. The longest high quality waveguides (up to 1m) are also reported. Experiments reveal that Gorilla Glass seems to be an ideal glass to write waveguides just below the surface, which is of great interest in sensing applications.

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1. Introduction

Many people have seen Corning's video: *A Day Made of Glass*, recently launched on Youtube [1]. Corning shows how the future can be seen using glass. According to them, Touch Screens will be everywhere. In particular, they envision transparent smart phones and tablets. Even today, many transparent displays have been fabricated using different technologies and several photonic devices have been made using transparent materials. To initiate the path to transparent smart phones, photonic devices must be fabricated in the glass protecting the display. Most smart phones and tablets use Corning Gorilla Glass as a protective screen due to its excellent mechanical and optical properties. This paper demonstrates the first high quality waveguides fabricated in this glass type using femtosecond (fs) lasers. Moreover, we found that Gorilla Glass is currently the most suitable material for laser writing of waveguides, especially for 3D devices. This is of great interest in prototyping photonic devices, and opens the door to high density optoelectronic integration directly in it.

Presently, the number of devices and tools in smart phones are limited by their size. Some electronic devices may be integrated in the glass screen in order to allow for more space in the smart phone, which could in turn host more tools, and indeed, as we will show, novel optical devices can also be integrated in the screen. In this paper, some photonic devices are proposed and demonstrated, and their fabrication described.

2. Waveguides in smart phone screens

A few technologies are currently available to fabricate waveguides in glass. It is, however, believed that laser writing is the best process for this application. First, waveguides fabricated using lasers are invisible to the naked eye, as seen in Fig. 1. Their fabrication can be easily included as part of the manufacturing steps of any smart phone currently on the market. Laser writing is a very simple, quick and cheap process: the waveguide fabricated in Fig. 1 took less than 10 seconds to write. Programming codes for the 3-axes motorized stages to set the waveguides path is quick, easy and is a one-step process. No additional cost from the initial laser writing setup is needed. On the other hand, waveguide fabrication techniques such as ion exchange or the in-diffusion process [2–8], are achieved with phase masks and numerous expensive steps of photolithography inside clean room facilities. Ultimately, laser writing is the only technology which allows 3D waveguides to be inscribed, a very valuable capability for smart phone applications as it permits stacking of device layers.

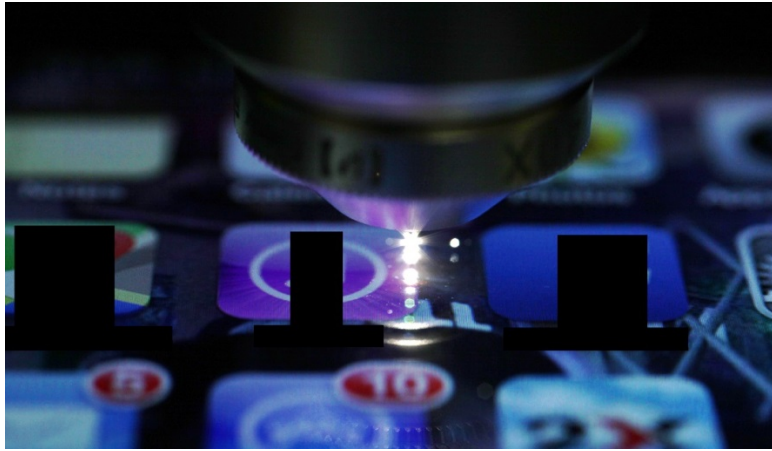


Fig. 1. Laser writing of a photonic device in a smart phone screen. The photograph shows that the waveguide (a horizontal line from the left side) cannot be seen by the naked eye. The white light comes from the plasma generated by the nonlinear absorption of the focused laser.

Following the pioneering work by Hirao's group [9, 10] in 1996, many studies have been published on femtosecond laser writing of optical waveguides in different types of glasses. To date, the lowest loss glass waveguide ever created using a fs laser was reported by Hirao *et al.* in 1998, achieving ~ 0.1 dB/cm at a wavelength of 800 nm [11]. Another notable report was conducted by Eaton *et al.* in 2005, with ~ 0.2 dB/cm of measured loss at a standard telecommunication wavelength of 1550 nm. This loss is unfortunately far too high for a number of applications, since it is an order of magnitude higher than that achieved with other techniques [12], and therefore remains a real barrier to their deployment and use.

Nonlinear absorption in transparent materials occurs via multi-photon interactions at intensities in the vicinity of 10^{13} W/cm², which for an impulse of 100 fs corresponds to energy densities of about a J/cm² [13]. Around this energy density, light is seen from the generated plasma, as shown in Fig. 1, and a photo-induced refractive index change occurs. When focusing lower energies, there is no nonlinear absorption and no material alteration or plasma is observable. Higher energies result in internal cavities or direct material ablation. Thus, there are parameters which need to be optimised to induce waveguides. Fabricating waveguides using femtosecond lasers is simple: an fs laser with an average power of ~ 1 W, a focusing lens and a 3-axes motorized stage are the three basic components required. However, there are several parameters to tune: power, wavelength, repetition rate, pulse width, focusing lens (beam waist size), scan speed, number of scan, polarization, beam shape, depth of writing, etc. The combination of all these parameters produces a large number of

writing conditions, from which a recipe that produces the best results has been determined by examining a large number of fabricated waveguides.

3. Experimental results

3.1 Low loss waveguides

Following our previous preliminary results on writing waveguides in Gorilla Glass [14], thousands additional waveguides were written using different parameters: writing power was varied from 200 to 1000 mW, the repetition rate from 300 to 1000 kHz, the scan speed from 0.1 to 300 mm/s, with a depth of writing up to 300 μm , using a $40\times$ (NA = 0.55) or $60\times$ (NA = 0.65) lens. All of the waveguides were fabricated in a single laser scan. Two fs lasers were used: a 1030 nm wavelength Altos Pharos laser, and a 1064 nm wavelength, Fianium FP1060-2 μJ -fs laser. The best overall recipe to achieve the lowest loss waveguides was found using the Pharos laser with a power of 600 mW, a repetition rate of 600 kHz, a pulse width of 300 fs, a $40\times$ focusing lens with a numerical aperture (NA) of 0.55, in a single scan at a speed of 10 mm/s with circularly polarized light. The waveguide was fabricated 150 μm under the surface of the glass. This particular waveguide exhibited a loss of 0.027 dB/cm at 1550 nm. To our knowledge, this is the lowest loss ever measured through a fs laser fabricated waveguide (see section 4 for details on loss measurement). The waveguide is shown in Fig. 2(a). The external region has dimensions of $50\times 67\ \mu\text{m}$ and the internal region, of $13\times 44\ \mu\text{m}$. It is believed that the internal region is mainly formed by the pulse's electric field and the external region by the heat accumulation and thus, stress relief. The modes supported by this multimode waveguide seem to be LP_{01} , LP_{11} , LP_{21} and LP_{41} . The near-fields give mode sizes of approximately $25\times 32\ \mu\text{m}$, which suggest that the fundamental mode travels through the internal region and the higher modes through the external region.

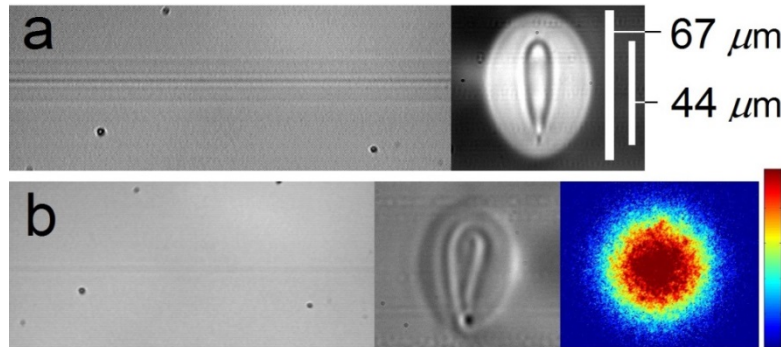


Fig. 2. Waveguides in Corning Gorilla Glass fabricated using a fs laser writing technique. Top and facet views of the 0.027 dB/cm loss multimode waveguide (a) and the 0.053 dB/cm loss singlemode waveguide (b). The near-field of the single-mode waveguide is also shown.

Certain applications need to use single-mode waveguides to avoid mode mismatch. An interferometer based temperature sensor that will be discussed later, is an example. In order to reduce the number of guided modes, two standard parameters need to be controlled: the refractive index difference between the core and the cladding, Δn , of the waveguide, and the waveguide core diameter, so that the v -value for a waveguide in a cylindrical geometry remains below 2.405 [15]. Curved or waveguides with bends, which are important for future applications, generate higher losses when the Δn is low. It is also not easy to control and measure the refractive index change from the fs laser interaction. On the other hand, the waveguide diameter is easily seen under the microscope. To reduce the diameter, one can reduce the power or increase the speed of laser scan. Reducing the power was not a practical solution in our case as the power needed to obtain nonlinear absorption is too high. The repetition rate of the laser Altos Pharos can be set between 1 kHz and 600 kHz. The scan

speed needed to make a single-mode waveguide was found to be too high, thus the distance between two laser pulses was found to be too long and, therefore, the refractive index change induced in the glass was periodic: i.e. instead of a waveguide, there was a periodic change in refractive index. Note that this phenomenon can be used to fabricate Bragg gratings [16, 17]. Single-mode waveguide fabrication was also possible using the Fianium fs laser due to its higher repetition rate compared to the Altos. The best single-mode waveguide was fabricated using the following parameters: power of 630 mW, repetition rate of 1 MHz, pulse width of 500 fs, $40\times$ focusing lens with a numerical aperture (NA) of 0.55, one scan at a speed of 300 mm/s with a circularly polarized light. The waveguide was located 150 μm under the surface of the glass. This waveguide exhibits a loss of 0.053 dB/cm; again, to our knowledge, the lowest loss ever measured for a single-mode waveguide fabricated using fs laser inscription. It is also the fastest fabrication process among all the existing methods reported so far [18].

Figure 2(b) shows the single-mode waveguide. The size of the external region of the waveguide is $\sim 37\times 53\ \mu\text{m}$, which is significantly smaller than for the multimode waveguide. The size of the internal region is $\sim 13\times 35\ \mu\text{m}$, similar to that found in the multimode waveguide. The circular near-field mode profile diameter is 11 μm , which confirms that the light is confined only in the internal region. Note that all the waveguides we fabricated had an oval shape. Nevertheless, a circular shape may be achieved by using a cylindrical lens [19, 20] or a slit [21, 22] which generates an elliptic beam just before the focusing lens. In addition, a low loss multimode waveguide written using the Fianium laser with the same parameters used with the Pharos laser at a scan speed of 10 mm/s gave a measured loss of only 0.08 dB/cm.

To prove that these results can be reproduced on tablets and other larger multimedia devices, 30 cm long straight waveguides were fabricated in Gorilla Glass using the same three recipes. Identical losses were measured. To our knowledge, these are the longest straight waveguide ever fabricated using a fs laser. Using the 0.027 dB/cm loss recipe, we fabricated a one-meter-long curved waveguide. This waveguide has an “S” shape: first in a straight line of 25.1 cm, followed by a half circle of radius 4.75 cm, a straight line of 20.1 cm, then another half circle with a radius of 4.75 cm and finally a straight line of 25.1 cm. This waveguide is the longest curved waveguide ever fabricated. The total measured loss was 24 dB. From this we can obtain the loss generated by the curve to be 0.38 dB/cm, which is significantly higher than for the straight waveguides. The average loss for the 1m long waveguide was still only 0.24dB/cm.

We also fabricated a few simple devices in Gorilla Glass (50%/50% coupler, 75%/25% coupler, 1×2 and 1×4 splitters) and all resulted in an additional loss of less than 0,5 dB over the entire device. The curvature needed to separate two waveguides requires a deviation of only 100 μm over a certain distance needed to form the couplers which only generates relatively low loss. However, certain applications such as loop cavity resonators or Sagnac interferometers need a curve over a relatively long distance. Note that the Sagnac interferometer is used to measure angular velocity [23, 24], which is of great interest for mobile multimedia devices. Even if 3D laser writing allows helical waveguide where the number of loops, N , multiplies the Sagnac effect per turn, small multimedia devices still need tight bends. For this purpose, we studied the loss as a function of radius of curvature. For a 5 cm radius of curvature, we obtained 0.7 dB/cm, for 4 cm: 1.2 dB/cm and for 3 cm: 2.4 dB/cm. All of these were measured over a quarter circle. These results show that there is a great opportunity for improvement. Increasing the refractive index of the waveguide would solve this issue. It is believed that inducing lower refractive index on either side of a waveguide using higher laser power (which would compress the waveguide) may prove to be a solution. However, this may be visible to the naked eye. Nevertheless, this method could be a solution in the glass surrounding the display area.

3.2 Explanation of the low loss in Gorilla Glass waveguides

The intriguing question raised with the measurements in our waveguides is: why is the loss so low? We propose that the induced index change in Gorilla Glass is highly dependent on the high internal stress of the Gorilla Glass. Rather than being a simple damage induced refractive index change, stress relief as in the case of type IIA index change in fiber Bragg grating could also participate in the process [25, 26]. In the case of the fiber, accumulated stress between the core and the cladding of certain types of fiber is released during grating inscription, inducing a negative index change around the core, allowing much stronger index modulation. In the present case, stress relief would induce a lower index region around the waveguide that would further enhance the guiding properties without the need of higher laser power which creates defects. This could explain the significantly lower loss induced in Gorilla Glass compared to other glasses.

We also propose that low loss waveguides in Gorilla Glass could be due to the quality of the core-cladding interface. Interface roughness generates losses as roughness induces scatter. It is believed that the alkali (potassium) ions in the Gorilla Glass soften this interface by filling in the irregularities. The two assumptions put henceforth, however, require confirmation with further investigation. Precise determination of the refractive index profile of the two waveguide section areas (parallel and perpendicular) could possibly help confirm our model. The depth of the alkali layer and its compression can be modified as a function of time and temperature of the chemical process. An opportunity for improvement should therefore be possible.

3.3 Three dimensional and surface waveguides

Three dimensional laser writing provides the possibility to fabricate compact devices. A compressed strong layer each side of the Gorilla Glass protects the glass from ablation and allows waveguide writing closer to the surface. Figure 3 shows the facet view of waveguides written close to the surface of Gorilla Glass [Fig. 3(c) and 3(d)] as well as standard Corning 0215 soda-lime glass [Fig. 3(a) and 3(b)], using the same writing conditions. Note that soda-lime glass is probably the most commonly manufactured glass, as it is used to make windows, bottles and numerous of other commercial products. Even 25 μm below the glass surface, the Gorilla Glass does not show any difference from deeper written waveguides [Fig. 3(c)]. On the other hand, soda-lime glass cracks easily and ablates [Fig. 3(a)]. Even when the top of the waveguide touches the glass surface, the Gorilla Glass waveguide is in good condition showing only 5% higher measured loss [Fig. 3(d)], while ablation occurs in soda-lime glass [Fig. 3(b)]. Note that for optimizing waveguides at different depths of writing, the writing parameters must be optimized slightly [27]. Figures 3(f) and 3(h) are the circular near-field mode profiles of the surface waveguides shown in Figs. 3 (c) and 3(d) respectively. To see how close to the surface those near-field modes are, higher laser power has been launched in the waveguides, see Figs. 3(e) and 3(g). We were unsuccessful in writing waveguides in soda-lime glass so close to the surface. Writing always resulted in cracking of the surface. These experiments reveal that Gorilla Glass seems to be an ideal glass to write waveguides just below the surface, which is of great interest in sensing applications.

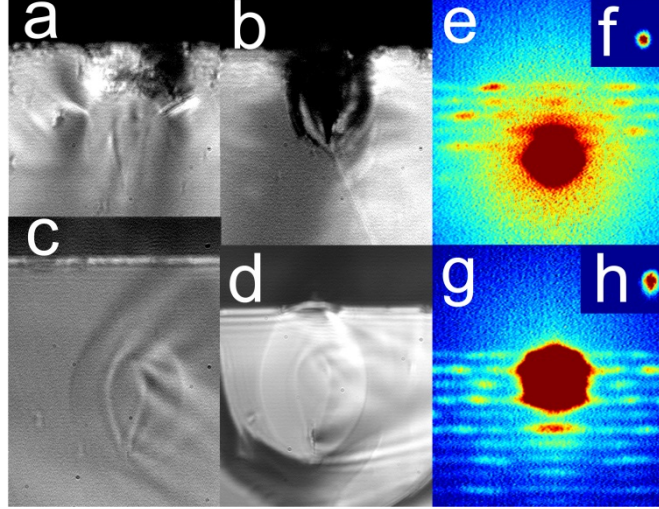


Fig. 3. Facet view of waveguides written close to the surface of standard Corning 0215 soda-lime glass (a and b) as well as Gorilla Glass (c and d), using the same writing conditions. a and c: 25 μm under the surface. Near-field mode profiles of the Gorilla Glass waveguides 25 μm under the surface (e and f), and touching the surface (g and h).

3.4 Temperature sensors in Gorilla Glass

Our first complete device fabricated in Gorilla Glass was a Mach-Zehnder interferometer (MZI) based temperature sensor. This very precise device is well known and has already been fabricated in different glasses using lasers [13], however none with laser written, *low loss* waveguides. The MZI is made of a straight waveguide and another curved waveguide as shown in Figs. 4(a) and 4(b). The optical path difference between the two arms is $nd = 480 \mu\text{m}$. A part of the MZI output spectrum at room temperature is shown in Fig. 4(c). The light intensity at the output of an MZI is calculated using the following formula:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left(\frac{2\pi nd}{\lambda}\right) \quad (1)$$

where I_1 and I_2 are the light intensities in the two MZI arms. The thermal expansion coefficient of the Gorilla Glass is $9.1 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ [28], which is about nine times that of the silica [29]. This means that the intensity change at the output is the same as a silica based device but in a smaller footprint. Using Eq. (1), the thermal coefficient and the path difference, we can obtain the wavelength shift in the spectrum. The red dashed curve in Fig. 4(b) is the theoretical spectrum after increasing the temperature by 10°C . The theoretically calculated values seem to agree with the experimental measurements, which were made using a heat gun; therefore, the precise setting of temperature was not easy to obtain. This wavelength shift can be easily obtained by measuring the output power from a monochromatic light source.

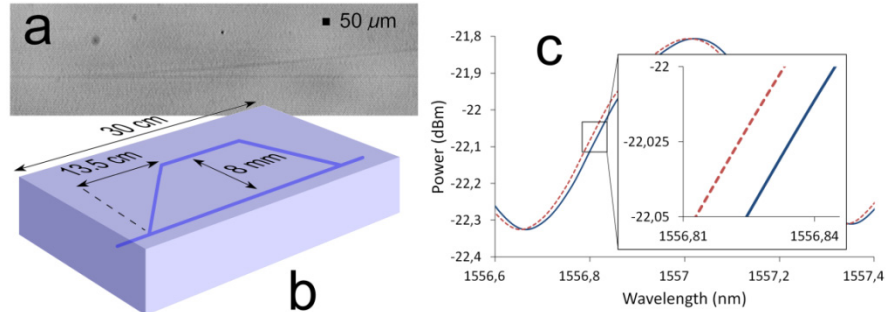


Fig. 4. (a) Top view of the splitting part at the MZI entrance. (b) Schematic of the MZI. (c) Spectrum of the MZI at 22°C (full blue curve) and at 32°C (red dashed line).

The MZI precision can be enhanced by increasing the contrast, also called visibility v , of the fringes at the output:

$$v = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} \quad (2)$$

To maximize the visibility, the intensity in the two MZI arms must be identical. To obtain this result, the MZI input coupler [Fig. 4(a)] should be symmetric. An application of this temperature sensor could be to detect overheating in a mobile multimedia device. In our current demonstration, the MZI is very long (almost 300mm); despite this, the loss is sufficient low for the device to operate easily. It is, of course, possible to make the device much smaller for *smart phone* applications.

3.5 Authentication security system for smart phones

We also fabricated another device that we believe could be useful for future mobile devices. The illegal cloning of smart cards is increasing and becoming routine and widespread by scanning using non-contact means. The trend in smart phones technology is to integrate features from different technologies (internet, camera, telephony...) and authentication will most likely be included in futures high end smart phones. Therefore, to further improve security, biometrics such as eye or finger print scanning technology can be used to add another level of security, however, these schemes may prove to be too complicated to become mainstream in the hardware of devices.

We propose a simple technique which can be integrated into a smart phone to improve authentication security. In our scheme, smart phone identification is based on simple optically encoded information in the screen of a cell phone, using a unique waveguide written into it. The spatially encoded image integrated into the waveguide as will be discussed below, may be read out optically using an infrared camera. The encoded information can be randomly generated using random numbers. The bend radius, along with the higher associated loss, may also be used in conjunction with the encoded information for encryption.

We used a fluorescent sheet placed in front of a CCD camera to detect the infrared light scattered out of an encoded waveguide. This poor detector obliged us to fabricate a high scattering loss region to demonstrate the concept. Figure 5 shows the encoded equivalent of the standard emergency Morse code "SOS": three dots, three dashes, followed by three dots. Each dot has been fabricated simply by pausing the laser at the relevant position for a second. The distance between two consecutive dots is 200 μm . On their own, these scattering dots can generate a large number of keys in a small area. Conservatively, for example, writing a dot (or not) every 100 μm could generate over 10^{15} different keys in a 1 mm^2 area. A total insertion loss of 10dB is estimated given a loss of 0.2dB/scattering point for the worst case of an all 1's key. Furthermore, the use of curved waveguides, splitters, Bragg gratings,

wavelength-division multiplexers (WDM) and demultiplexers to separate the wavelengths, could render these keys very complex.

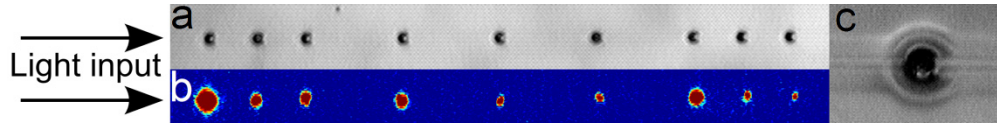


Fig. 5. a: Microscope top view of a waveguide with scattering spots. b: Infrared top view of the same waveguide when 1550 nm light is launched into it. These spots are made by focusing the fs laser for a second at a point. c: Zoom in of a spot showing the waveguide and the micro-hole created.

4. Methods for loss measurements and discussion

Three methods were used to make loss measurement to ensure accurate results. First, an optical backscatter reflectometer (OBR) from LUNA was used. The OBR sends a laser pulse and measures the light scattered back as a function of time, which is then converted into a time delay and therefore, position. Figure 6 shows the response of the OBR after sending a pulse in the 30 cm long multimode waveguide fabricated using the Pharos Altos fs laser. The first peak on the left is the light reflected from the connection between a single-mode SMF28 fiber and the 30 cm waveguide. The second peak, 30 cm further (at 5.78m), is the reflection from the end facet of the waveguide. Note that the two small peaks at around 5.7 m are always present regardless of the sample or material, implying that these peaks come from a mode mismatch or multiple reflections in the instrument. The smoothness of the waveguide response tells us that the losses come from scattering and not from defects or other non-uniformities.

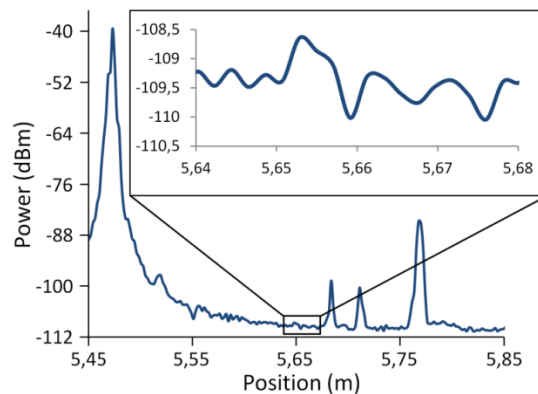


Fig. 6. Power response of the 30 cm multimode waveguide (with a loss of 0.027 dB/cm) using an optical backscatter reflectometer (OBR) as a function of the distance. The zoomed-in part is used to measure the loss of the waveguide.

If a material is homogeneous, which is the case for Gorilla Glass, the propagation loss in dB/cm can be obtained through the slope of the back-scatter curve. As the laser pulse from the OBR has a certain width, it has an effect before and after a connection, so that only devices longer than ~50 cm can be analyzed adequately. Our waveguide was not long enough to avoid the large artifact at the waveguide entrance. Therefore, the loss obtained was higher than the real value (measured by the cut-back method) but gives us a good approximation. A loss of 0.06 ± 0.04 dB/cm at 1550 nm was obtained by zooming-into the graph [Fig. 6]. Note that the slope gives us twice the loss as the light passes twice through the waveguide due to the backscatter. Also the optical fiber used to couple the light in the multimode waveguide, can excite higher order modes and in turn generate additional loss.

The second technique used to measure loss was by the insertion loss of the entire waveguide - measuring the power at the input and subtracting the power at the output. Unfortunately, this method includes the Fresnel and the coupling loss. To minimize the coupling losses, a lens system was used in order to find the best numerical aperture (NA) for our waveguide. Figure 7 shows the loss and the additional modes that appear as the NA increases. With an NA of 0.25, each mode can be excited by simply altering the launch conditions and a loss of 0.23 dB/cm is measured. However, with a lower NA, the higher order mode LP_{41} disappears and the loss, surprisingly, reduces to between 0.1 and 0.15 dB/cm. By reducing the NA further to 0.045, we obtained even lower losses of 0.04 dB/cm, with only the LP_{01} and LP_{11} modes present. An approximation using the waveguide output light angle gives an NA of 0.03 ± 0.01 . To reach such an NA, we used 150 microns diameter pin hole, which gave an NA of ~ 0.012 . Unfortunately, most of the light was blocked and the fluctuation on the power meter increased. Therefore, for this measurement, a loss of 0.03 ± 0.02 dB/cm, is a best estimate. Note that no index matching oil can be used with the lens coupling technique; no anti-reflection coating was used on the polished facets either to eliminate the Fresnel losses. Depending on the polishing quality, ~ 0.1 to 1 dB/facet is usually subtracted from the total loss. To polish our samples, we used different polishing sheets down to a grit size of 0.3 μm . The staircase shape of the curve shown in Fig. 7 was seen in all waveguides fabricated using different laser writing parameters.

An approximation of the refractive index variation of the waveguide $\Delta n = n_2 - n_1 = 0.0003 \pm 0.0002$ (n_1 = cladding refractive index, n_2 = core refractive index) is calculated using the refractive index of the Gorilla Glass $n_1 = 1.503175$ [28] and the following formula:

$$NA \approx \sqrt{n_2^2 - n_1^2} \quad (3)$$

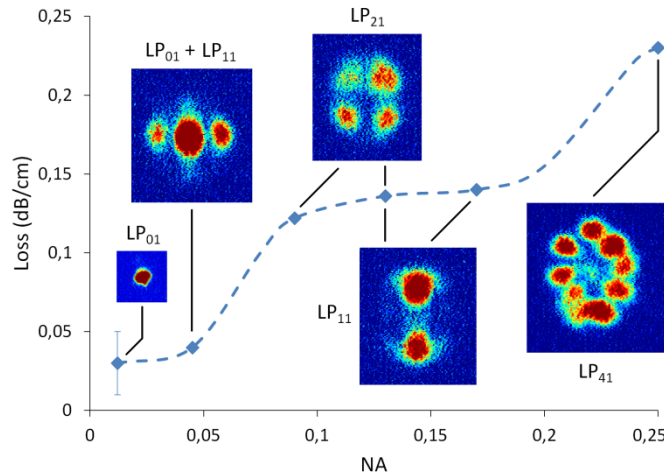


Fig. 7. Loss of the 30 cm multimode waveguide (with a loss of 0.027 dB/cm) with different launch NAs. More modes appear as the NA increases. At an NA of ~ 0.012 , only the LP_{01} mode is seen, and at an NA of 0.25 all modes are seen at the waveguide output by altering the launch conditions.

The third loss measurement method used is the well-known cut-back method. This method involves comparing the optical power transmitted through a long waveguide to the power transmitted through the shorter piece after cutting the waveguide. The loss in dB over the cut-off length gives the exact propagation loss excluding Fresnel reflections. A 300 mm long waveguide was cut to a 230 mm and then to a 70 mm length. Using these two pieces and comparing each one to the 300 mm long waveguide, we obtained a loss of 0.027 dB/cm. This technique is known as the most accurate but is not usually used as it is destructive. However,

this was not an issue for our team as the fabrication of waveguide using the laser is very fast. To avoid any polishing non-uniformities or other problems which could have affected the results, we repeated the measurement on two other samples and obtained similar results. In the literature, 10 to 50 mm long waveguides are usually fabricated and the cut-back technique is therefore not at all accurate. This technique becomes extremely powerful applied to our longer 30 cm long devices, providing very accurate data for the first time.

5. Conclusion

We have shown that it is possible to write very low loss waveguides in Gorilla Glass using fs laser pulse inscription, we believe, for the first time, achieving record propagation losses of $<0.03\text{dB/cm}$. We have demonstrated that there is a mode-dependent loss present in fs laser written waveguides for the first time. Exciting the lowest order mode gives the lowest loss for the waveguide, but with a low NA. It may be possible to improve the NA by the judicious use of the laser to embed lower refractive index regions close to the waveguide. The stress profile of the Gorilla Glass, appears to assist in the reduction of loss, which we believe is primarily due to reduced scatter. Also for the first time, we believe we have shown that these waveguides may be written just below the glass surface in Gorilla Glass, probably assisted by the stress profile, not possible in other glasses due to ablation problems. Further, we have written ultra-long waveguides, up to 1m long in this glass, demonstrating the possibility of integrating photonic devices into multimedia glass, such as smart phones and displays. Indeed, the encoding of information, we believe, is also a novel technique for encryption in waveguides. Also demonstrated is an interferometric MZI device capable of sensing temperature in the same glass, opening possibilities of making the Smart Phone Smarter with Photonics (SPSP).

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