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Guiding losses estimation in hydrogel-based waveguides

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Guiding losses estimation in hydrogel-based waveguides

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Abstract. A method based on the photographic recording of the power distribution laterally diffused by cationic electroactive network (CN)-based hydrogel waveguides is first checked against the well-established cut-back method and then used to determine the different contributions to the optical power attenuation along the hydrogel-based waveguide. Absorption and scattering loss coefficients are determined for 450 nm, 532 nm and 633 nm excitation.

1. Introduction

Optogenetics and photonic technologies are changing the near future of medicine. This new technology promotes the progress of early detection and diagnosis of diseases, as well as the possibility of a better understanding of biological systems. [1,2] In order to implement these light-based therapies, patient-friendly devices that can deliver light inside the body while offering tunable properties and compatibility with soft tissues are needed. The sensitivity and selectivity of the optical responses are strongly on the characteristics of elements of optical devices, such as an optical waveguide. In this context, soft polymeric biomaterials have been used as alternatives to silica for fabricating optical waveguides. [3] Among these materials, optical waveguides based on hydrogels are arousing great, as they allow the distribution of light several centimeters deep in human tissues, without causing damage to the patient. [4,5] Hydrogels show excellent properties such as flexibility and biocompatibility. Their optical and mechanical properties can be fine controlled by adjusting their polymer content, polymer chain length as well as molecular weights. Moreover, the refractive index and thus its waveguide behaviour can be modulated depending on the water content. Finally, variation in pore size, temperature, pH, ion concentration, degree of crosslinking, ligand attachment, and interaction with other molecules give them interesting properties.

A key parameter to determine its capability to conduct the light efficiently and its applicability is the attenuation experienced by the optical power along the waveguide. The well-established cut-off method, in which the output power is measured for progressively shorter waveguide lengths, has a number of drawbacks: it is destructive; it requires a long enough sample and a certain time to prepare the measurement after each and every cut. Taking into account that its implementation is much more delicate compared to measurements in optical fibres, for which very precise equipment is available in order to cut them or connect them in a repetitive way. In contrast, no commercial machine is available to cut a hydrogel sample, nor connectors are available to plug them into a light source or into an optical detector, in a repetitive way. One of the aims of this work is to explore the possibility of measuring the attenuation in hydrogel waveguides through a photographic record of the power distribution laterally diffused by the inhomogeneities of the material, assumed to be proportional to the guided power in the longitudinal direction. With this method, referred to from now on as the photographic one, there is no need for cutting and realigning the setup, thus eliminating a significant source of measurement uncertainty and, besides, employing a non-destructive procedure.

In the first part of the paper, the details of the photographic method are provided. A comparison between attenuation measurements obtained by both methods is included, in order to check the reliability of the alternative procedure. In the second part, several attenuation measurements at different wavelengths are shown which, together with an absorbance measurement, allows one to uncouple the different contributions to the propagation losses.

2. Photographic and cut-off methods: comparison

The hydrogels used were based on a cationic electroactive network (CN), Figure 1, previously reported by Martín-Pacheco *et al*.[6] (Scheme 1) with application in the field of soft robotics[7] and with self-healing ability.[8] This kind of hydrogel is able to retain a certain and constant amount of water in its 3D polymer structure at ambient conditions (25 °C, 1 atm), reaching an “equilibrated” state, and remaining stable. Thus, considering that, measurements were performed in this state in order to have a reproducible system.

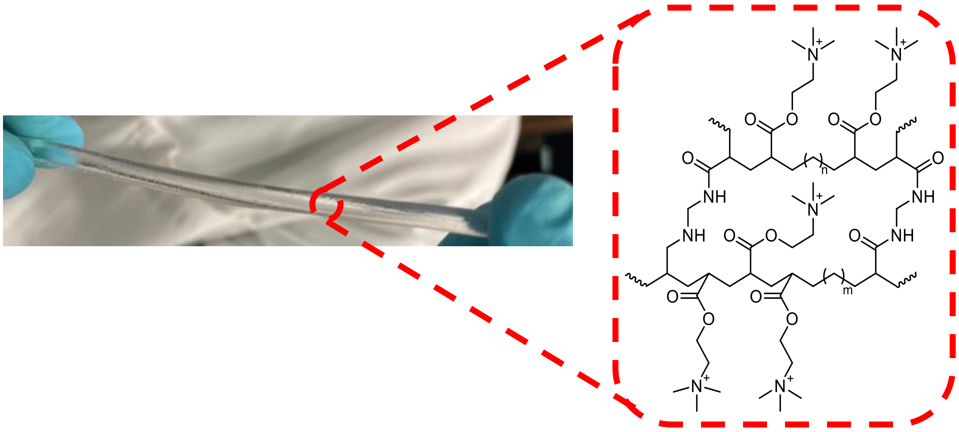

Figure 1. Chemical structure of the CN hydrogel and photo of the hydrogel cylinder used

A scheme of the experimental setup for implementation of the photographic method is shown in Fig. 2 [A]. The hydrogel samples are cylinder-shaped, with diameters between 3 mm and 4 mm and lengths between 6 cm and 10 cm. At the moment of the measurement, each sample is kept fixed and straight by placing it on the groove of a suitable piece (not shown in the scheme). The sample receives light from a laser. Three of them have been employed in this work, centered at 450 nm, 532 nm and 630 nm. Images of the illuminated sample were taken by means of a computer-controlled Canon EOS 1000D camera, allowing independent detection in the R, G and B channels. For each sample, pictures were taken, seeking maximum contrast without reaching saturation. In order to achieve so, apart from the camera parameters such as exposure time, ISO and aperture, also the input laser power was modified, within the range of a few mWs. Figure 2[B] shows an example of the pictures obtained.

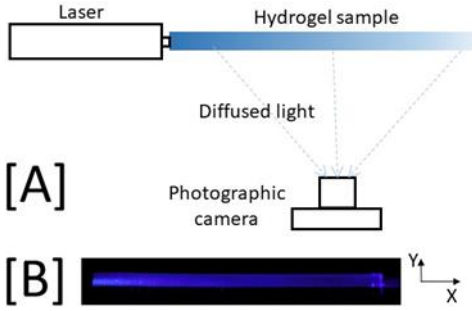

Figure 2 – [A]: Scheme of the experimental setup. Sizes and distances are not drawn to scale. [B] – Picture of a hydrogel sample fed at its left end with the laser centered at 450 nm. The coordinate system to be employed is specified later.

In order to extract the longitudinal optical intensity distribution from each picture, several operations are performed. First, an area of the picture is selected, avoiding the section close to the laser input, where coupling effects may give rise to an undesired contribution to lateral light, and in general, both saturated and very dark regions are also discarded. Besides, it is convenient to avoid brilliant points corresponding to damaged spots caused by sample manipulation. The area selected determines a set of M x N pixels, M and N being the number of pixels selected in the X and Y directions, respectively (see Fig. 2[B]). We pay attention to the information they contain at the channel corresponding to the laser wavelength employed (R for 632 nm, G for 532 nm and B for 450 nm). This information is a number between 0 and 255, not proportional to but directly correlated with the light energy received by the pixel. By application of a transform inverse to the one shown in [9], we obtain a matrix of N x M values proportional to the relative exposure received at each pixel of the selected region. Finally, in order to reduce noise cause by surface imperfections, the N values corresponding to each matrix column are averaged so that an array of M values is obtained. There was the option of selecting directly an M x 1 array of pixels, but we have checked that considering an M x N matrix and performing a transversal average is worthwhile, as it provides a significant noise reduction.

On the other hand, the correlation between pixel position at the image and coordinate at the object can be easily obtained by means of a picture of two points aligned with the X axis and whose distance is measurable. Figure 3 shows an example of the relative exposure obtained for 450 nm excitation. Results are fitted to an exponential function $P(x) = P_o \exp(-bx)$, where P_o and b are the fitting parameters and, in particular, b represents the attenuation coefficient. The value obtained for the data in Figure 3 is $b=0.45 \text{ cm}^{-1}$.

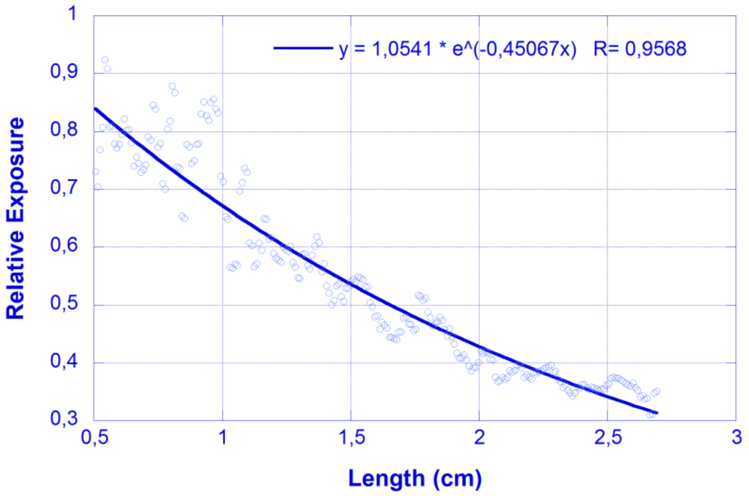

Figure 3 – Relative exposure vs. longitudinal coordinate (photographic method). Feeding laser @ 450 nm. Dots: experimental values; Solid line: fit to Beer-Lambert law.

A value b=0.47 cm^{-1} is obtained for this coefficient by means of the cut-off method, applied to a similar sample. Figure 4 shows the results obtained.

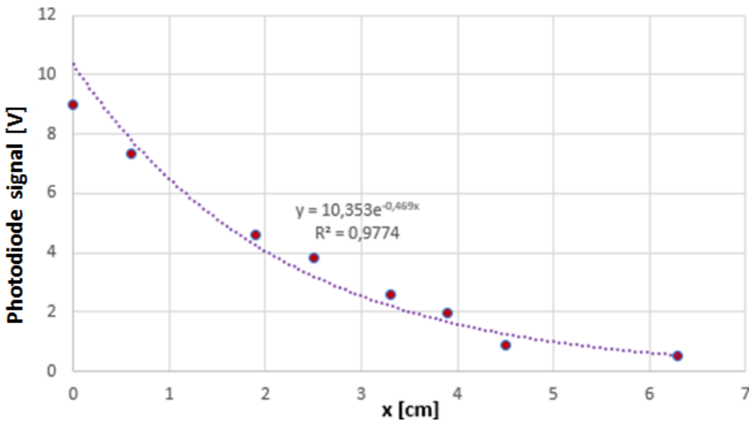

Figure 4 – Photodiode signal at the sample output end as a function of its length (x + 4 cm). Feeding laser @ 450 nm. Similar sample as employed in the photographic method.

The good agreement in the attenuation coefficients obtained by both methods definitely supports the validity of the photographic methods for attenuation measurements in these kinds of samples.

3. Measurements and analysis

The relative exposure distributions along the waveguide obtained when using the two other lasers to feed a similar sample are shown in Figure 5. The corresponding fittings provide b = 0.21 cm^{-1} (λ = 532 nm) and b = 0.07 cm^{-1} (λ = 632 nm).

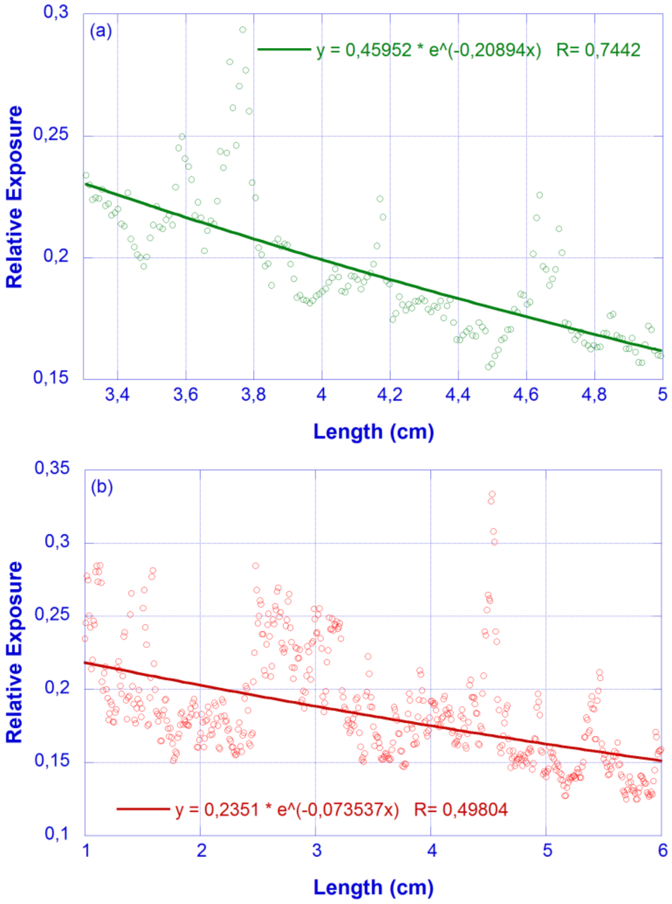

Figure 5.- Relative exposure vs x coordinate (photographic method). Feeding lasers: a) @ 532 nm (Green, top); b) 632 nm (red, bottom). Dots: experimental values; Solid line: fit to Beer-Lambert law.

These attenuation coefficients account for all the possible causes of losses, own of the material (absorption, scattering) or the guiding by the waveguide structure. In order to uncouple the different contributions, an absorbance spectrum on the hydrogel on which the sample is based has been measured (Figure 6).

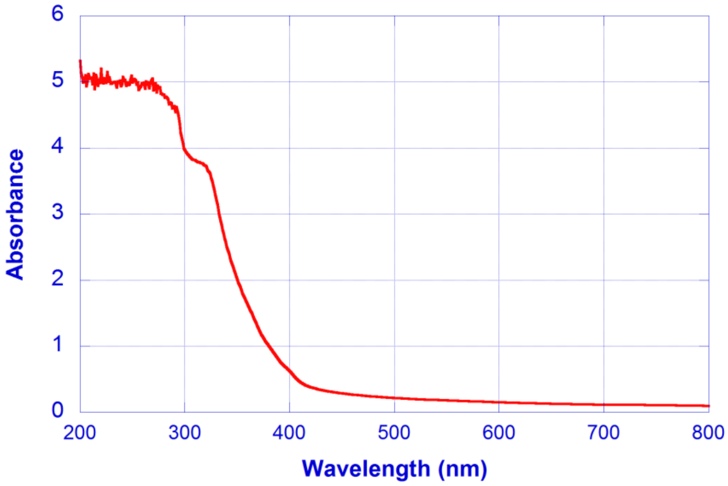

Figure 6.- Absorbance spectrum of the hydrogel of which the sample is composed

Taking into account the λ^{-4} scattering probability dependence according to Rayleigh law, it is possible to fit the three attenuation coefficients obtained so that the contributions to the losses of the guided optical power can be uncoupled. From the absorbance measurement shown in Fig. 5 a maximum background value has been assumed (that of 800 nm) and subtracted to the attenuation coefficients. A good numerical fit is obtained by just considering absorption and scattering losses so that any influence on loss of the guiding by the waveguide structure can be neglected. Table 1 shows the obtained results.

Table 1. Different contributions to attenuation at the three wavelengths employed (losses caused by the waveguide structure not shown because they turn out to be negligible).

Wavelength (nm)	Absorption losses (dB/cm)	Scattering losses (dB/cm)
450	1.78	0.17
532	0.83	0.09
633	0.26	0.04

4. Conclusions

A new method to determine the contributions to the attenuation of the optical power along a hydrogel-based waveguide has successfully been validated against the well-established but experimentally more demanding cut-back method. Using this new method it is found that only absorption and scattering losses are significant and their loss coefficients can be readily determined.

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