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Effects of cladding on the emission of doped plastic optical fibres

I. Bikandi[*,1], M. A. Illarramendi[1], J. Zubia[1], G. Aldabaldetreku[1], and L. Bazzana[2]

[1] School of Engineering, University of Basque Country UPV/EHU, Alda. Urquijo s/n, 48013 Bilbao, Spain
[2] Chemistry Department, Luceat S.p.A, Viale G. Marconi 31, 25020 Dello (BS), Italy

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* Corresponding author: e-mail inaki.bikandi@ehu.es, Phone: +0034 946017342, Fax: +0034 946014259

The effect of the cladding on the emission properties of doped plastic optical fibres has been analyzed by using the side-illumination technique. For that purpose, the photoluminescence spectra of cladded and uncladed plastic optical fibres, both with the same doped core material, have been compared. In particular, we study the dependence of the emitted intensity on the launching angle and on the propagation distance. We also analyze the angular distribution of the emitted light as a function of the propagation distance through the fibres. Using this information, we have characterized the optical losses in both kinds of optical fibres. The study has been performed in plastic optical fibres doped with a conjugated polymer.

1 Introduction With the development of plastic optical fibres (POFs) in the last years [1], increased research activities have also been carried out in the field of active POF amplifiers and lasers. POF amplifiers that generate signal light in the visible and near-infrared are potentially important because of their adaptability for POF-based short span optical local distribution networks. The advantage of using polymeric materials is that they are easy to fabricate, low cost, and they enable us to carry out a variety of optical functions by attaching active elements to the polymer system. Amplifiers with high gain and efficient lasers have been obtained with organic dye-doped POFs [2,3]. Conjugated polymers and related materials are being actively investigated as active dopants in plastic optical fibres (POFs) to provide amplification and switching capability [4,5]. Because of their large gain cross sections and little concentration quenching they are the ideal candidates for the manufacture of active media in POF networks. On the other hand, the transmission of radiation beams through optical fibres in a stable and uniform manner is a critical requirement in many laser and sensor applications. In such applications it is important to maintain high core to clad ratios for minimum penetration and maximum flexibility.

The aim of this work is to analyze the effect of the cladding on the emission properties in plastic optical fibres doped with the conjugated polymer poly(9,9 '-dioctylfluorene-co-benzothiadiazole (F8BT). Particularly, we have studied the emission properties of cladded and uncladed plastic fibres, both with the same doped core material. We have measured the emitted intensity and its far field pattern (FFP) as a function of propagation distance through the two types of fibres by using the side-illumination technique. This method, based on transverse excitation for measuring the optical attenuation in doped fibres, was first proposed in 1999 by Kruhlak and Kuzyk [6,7]. Since the method is non-destructive, it constitutes an alternative technique to the traditional methods like the cutback method or the bulk measurement. It has been used to characterize the emission from doped polymer optical fibres [8,9] and to develop position sensors [10]. The dependence of the emitted intensity as a function of the launching conditions has also been measured and analyzed. From the analysis of the obtained measurements, we have characterized the optical loss in the two types of optical fibres.

2 Experimental In our experiments, we have investigated step-index cladded and uncladed plastic fibres. The core material in both fibres is the F8BT polyfluorene embedded in standard poly(methylmethacrylate) (PMMA)

plastic optical fibre with a concentration about 0.003wt%. The cladding material is not doped. The doped fibres were prepared at the plastic fibre manufacturer Luceat S.p.A (Italy). The preparation of the doped POF is depicted elsewhere [11]. Fibres were cut to 40-50 cm lengths, and the fibre ends were carefully polished by hand with polishing papers.

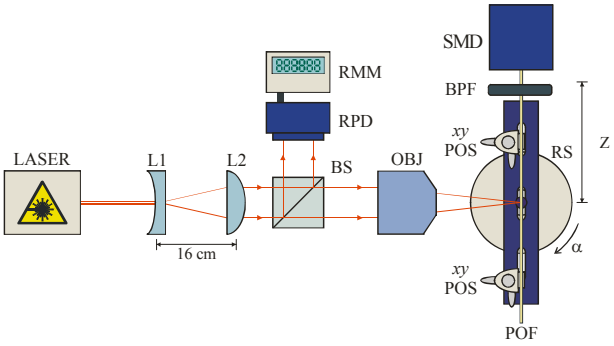

Figure 1 Experimental set-up used to measure the emission intensity and the FFP as a function of launching angle (α) and as a function of propagation distance (*z*). Legend: L1 and L2: lens; BS: beam splitter; OBJ: 0.1–NA objective; xy POS: xy–micropositioner; RS: rotation stage; RPD: reference photodetector; RMM: reference multimeter; BPF: band pass filter; SMD: signal measurement device.

Figure 1 shows the experimental set-up employed to measure the dependence of the emission on the launching angle (α) and on the propagation distance (*z*). A 379-nm-wavelength diode laser is used as the light source. The laser beam is collimated and expanded using lenses L1 and L2 before impinging laterally the active plastic optical fibre. The laser beam crosses a beam splitter in order to obtain a reference signal and cancel the laser light intensity fluctuations. The doped POF sample is held by two xy–micropositioners standing on a rotation stage. The automatized rotation stage, driven by a motion controller, allows us to change the launching angle in steps of 0.5 degrees, so that we are capable of performing an accurate angular scan of the fibre. Both the dependence of the emission intensity and the far field emission pattern on the propagation distance have been obtained replacing the rotatory stage by an automated long-range linear stage, so that the fibre can be moved transversely to the launching beam. The emission intensity is recorded by using a low-power Silicon Photodetector, an integrating sphere or a grating with charge-couple device (CCD) sensor array. All emission spectra measured have been corrected for the response of the detection system. The measurement of the FFP of the emission is obtained using the Hamamatsu LEPAS optical beam measurement system. A narrow bandpass filter centered at 520nm (± 2 nm) was placed at the entrance of the signal measurement detector in order to perform the measurements at a single emission wavelength. The absorption spectra of the fibres were recorded on a Cary 50 UV-Vis spectrophotometer equipped with a fibre optic coupler accessory. In these measurements the lengths of the fibres were about 1cm so that the absorption band of the dopant embedded in the fibre could be detected.

3 Results and discussion The absorption and emission bands of the F8BT doped cladded plastic optical fibre are shown in Fig. 2. The absorption spectrum of the F8BT doped fibres is described by the characteristic absorption bands of the PMMA matrix in the near infrared region together with an absorption band that peaks about 420 nm, which corresponds to the $S_0 \rightarrow S_1$ transition of the organic dopant embedded in the POF. It can be observed that the band corresponding to the dopant is superimposed on the UV absorption edge of the PMMA. Due to the very short lengths of measured fibres, the power mode distribution of the fibre has not yet reached the equilibrium condition, and consequently, the attenuation obtained may be higher than that obtained by using long segments as demanded by the standard cut-back method. Regarding the emission spectrum, it is characterized by a broad and featureless band that corresponds to the $S_1 \rightarrow S_2$ transition, peaking at 520 nm. There are no noticeable differences between the spectra of the cladded and uncladded fibres.

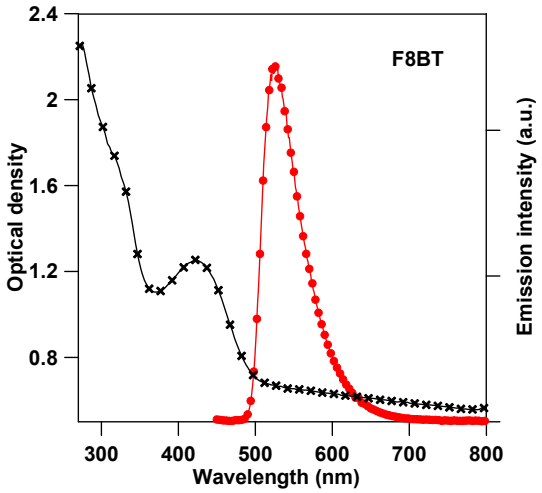

Figure 2 Absorption (–x–) and emission (– ● –) spectra of F8BT doped cladded fibre. The absorption and emission spectra are overlapped in the region 495-510 nm. The emission spectrum was obtained exciting the sample at λ_{ex} =379 nm.

The results of the angular scanning measurements exciting at the absorption band of the organic dye (λ_{ex}=379 nm) and outside of the absorption band (λ_{ex}=633 nm) are shown respectively in Figs. 3 (a) and (b). The symmetry of the measured values for the emission intensity at the output end of the fibre in Fig. 3(a) indicates that emission increases with the launching angle both in the forward and in the backward direction. This behaviour indicates that the

radiation pattern of the emission generated in the doped fibre core is isotropic, as it could be expected. Note that there is a minor difference in the results for the cladded and uncladded fibres. This can be due to the differences in the refractive-index profiles for the cladded and uncladded fibres. On the contrary, if the same angular scanning measurements are performed exciting out of the absorption band, significant differences in the response from the cladded and uncladded fibres are observed (see Fig. 3(b)). In this case, due to the geometry used in the excitation (side-illumination technique), the light detected at the end of the fibre is the scattered light that has been able to propagate through the fibre. The asymmetry of the curves is related to the radiation pattern of the scattering processes. It can be seen that as the launching angle increases in the forward direction, the slope for the uncladded fibres is higher than the slope for the cladded ones. This behaviour can be explained by considering that imperfections and roughness at the fibre interface are more noticeable and critical in the uncladded fibre [12].

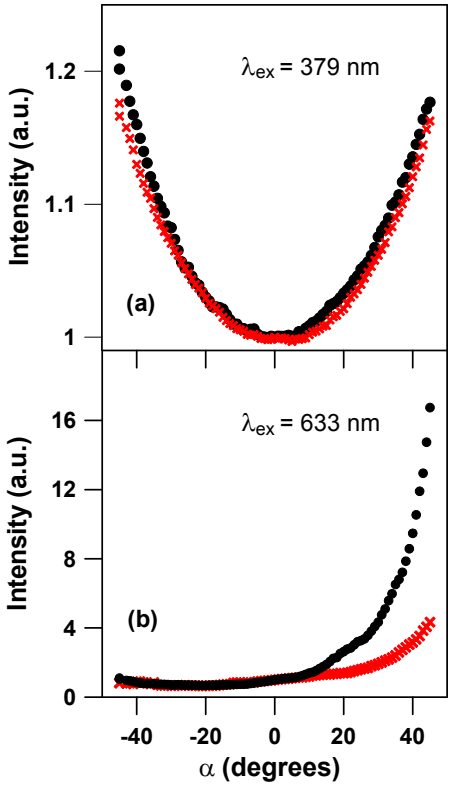

Figure 3 Emission intensity at the output end of cladded fibres (x) and uncladded fibres (●) as a function of launching angle (α). (a) Exciting at λ_{ex} =379 nm and detecting at λ_{em} =520 nm. (b) Exciting and detecting at λ_{ex} ==λ_{em} ==633nm. The propagation distance is 17cm in both curves.

The diminishing of the spectrally integrated intensity as a function of propagation distance through the cladded and uncladded fibres is displayed in Fig. 4. It is caused by the loss mechanisms such as absorption and scattering processes. It can be noticed that the intensity emitted from the cladded fibre is in average three times higher than the emitted from the uncladded one (see Fig. 4(a)). Besides, the decay of the intensity with distance is clearly lower when the fibre is surrounded by a cladding (see Fig. 4(b)). The solid lines in the Fig. 4(a) are the theoretical curves obtained by using a model which represents the light intensity after propagating a distance z from a point source [7]. Since it has been taken the same absorption coefficient for both fibres, the only difference between the theoretical curves is the complementary critical angle which is related to the refractive-indices [1,12]. In a more precise theory, we should take into account the re-absorption and re-emission phenomena that take place in the fibres [9]. However, these processes occur in the same way in both types of fibres studied, so there should not be differences between the curves due to these phenomena. As it can be seen, a good result is obtained for the curve corresponding to the cladded fibre, whereas the agreement between the theoretical and the experimental curves for the uncladded one is not so good. In this case, the decrease of the measured intensity is markedly higher than that calculated by the theoretical predictions. This indicates that, in addition to the refractive-index mismatch effect, there is another physical effect which is different in each fibre. This fact, which is the origin of the additional source of loss in the uncladded fibres, has not been taken into account in the theoretical prediction.

This behaviour has been corroborated by measuring the dependence on the propagation distance of the FFP of the emission at the output of the fibres. We can observe in Figure 5 that the angular distribution of the emission in the cladded fibres hardly varies in the range of propagation distance analyzed. On the contrary, in the uncladded fibres, the FFP measurement images show a diminishing of the angular distribution of the emission in the same range of distance. We can quantitatively analyze this behaviour by calculating the exit numerical aperture (NA_{FF}) from the measurements. This parameter, which is related to the complementary critical angle, is given by the sine of the half-angle at which the far field angular intensity distribution has decreased to 5% of its maximum value [13]. For the propagation distances studied (~ 10-30cm), NA_{FF} values for the cladded fibres do not change and are nearly 0.51 (±1) whereas NA_{FF} values in the cladded fibres decrease from 0.33 to 0.21. A decrease in the angular distribution of the emission is related to the optical losses [13].This could explain the extra losses observed in the measurements corresponding to the uncladded fibre which possibly are caused by roughness and imperfections at the core-air interface. The angular scanning measurements shown in Fig. 3(b) also pointed to this physical phenomenon.

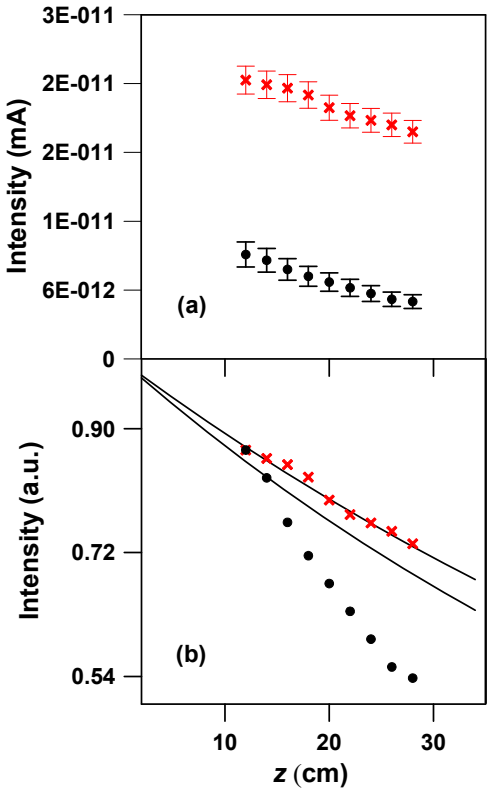

Figure 4 Emission intensity through cladded fibres (x) and uncladded fibres (●) as a function of the propagation distance (z). (a) Absolute intensities measured by an integrating sphere. (b) Experimental intensities normalized at z = 12 cm. The solid lines are the theoretical predictions obtained with n_{core} = 1.492, n_{cladd} = 1.412, n_{air} = 1 and an absorption coefficient $\alpha = 0.0011 mm^{-1}$.

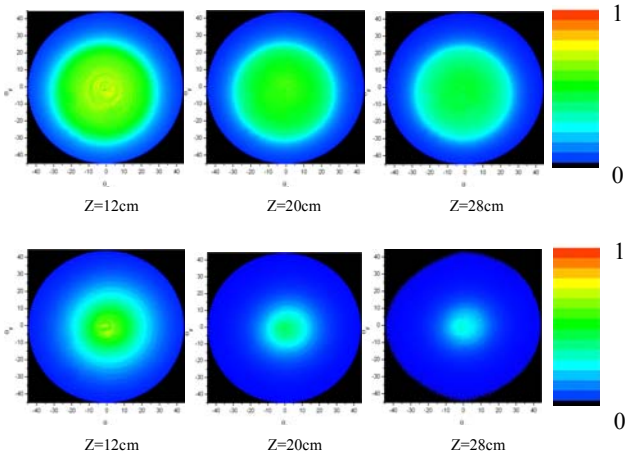

Figure 5 Dependence on the propagation distance (z) of the FFP of the emission at λ_{em} =520 nm in cladded (top images) and uncladded fibres (bottom images).

4 Conclusions The effects of the cladding on the emission of the F8BT dye doped plastic optical fibres have been analyzed by using the side-illumination technique. For propagation distances around 10-30 cm, the value of the emitted intensity is in average three times higher in the cladded fibres than in the uncladded ones and the decay of intensity with the distance is significantly higher in the uncladded fibres. For the same propagation distances the angular distribution of the emission is constant in the case of cladded fibres, whereas for the uncladded ones is decreasing. These experimental results can not be explained by assuming a model where the only physical difference between the two kinds of fibres is the different refractive index profile. Roughness and imperfections at the core-air interface compared with those at the core-cladding interface could result essential to explain the experimental behaviour.

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