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Loss characterization in rhodamine 6G doped polymer film waveguide by side illumination fluorescence

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Abstract
We report the position dependent tuning of fluorescence emission from rhodamine 6G doped polymethylmethacrylate film waveguide using a side illumination technique. The transmitted fluorescence as a function of the distance from the point of illumination is measured by translating the waveguide horizontally across a monochromatic light source. This technique has been utilized to characterize the optical loss in dye doped waveguides. We observe that the optical loss coefficients for shorter and longer distances of propagation through the dye doped waveguide are different. At longer distance of propagation a decrease in optical loss coefficient is observed.

Keywords: dye doped waveguide, fluorescence, attenuation

1. Introduction

In the field of photonics, considerable attention is centring on the use of polymer waveguides and fibres as they have a great potential for creating all-optical devices [1, 2]. The advantage of using polymeric materials is that they are easy to fabricate, low cost and enable us to carry out a variety of optical functions by attaching organic dyes to the polymer system. Polymers have higher efficiency, better beam quality and superior homogeneity [3]. Moreover, waveguide structure with its long interaction length of active material is attractive as it is effective for controlling optical signals with low input power. Polymer waveguides and fibres doped with organic dyes have proved to be potential candidates for use in fibre lasers and amplifiers [4–6]. By choosing appropriate dyes, we can obtain laser emission from doped polymer waveguides in the entire visible region. The combination of a signal processing function of optically active organic materials with a passive signal transmission function of transparent polymers has been used in the design of all-optical switches [7].

The properties of dye doped plastic waveguides should be clearly known before they are used as all-optical devices. The optical attenuation in these waveguides is an important parameter of interest. There are different techniques for measuring the propagation losses in waveguide structures. Usually the propagation loss in fibres and planar waveguide structures is measured by the cut-back technique [8, 9] which consists in comparing the transmittance of several guides with different lengths at a specific wavelength, or the loss is extrapolated from a bulk measurement. The disadvantage of the cut-back technique is that it is a destructive method. Bulk measurements involve a broadband light source incident upon a fixed length of material and a spectrometer to read the transmitted intensity. As an alternative to the above mentioned techniques, a non-destructive side illumination fluorescence technique for measuring the optical attenuation in dye doped fibres has been proposed by Kruhlak *et al* [10, 11]. In this paper we describe the use of this technique to characterize the loss mechanisms in dye doped planar waveguide structures. This measurement technique requires a monochromatic light source to illuminate the waveguide from the side. The fluorescence collected from one end of the waveguide is used as a light source to characterize the attenuation mechanisms in the planar waveguide structures.

2. Experimental details

Studies were carried out on chemically stabilized rhodamine 6G doped PMMA (polymethylmethacrylate) planar film

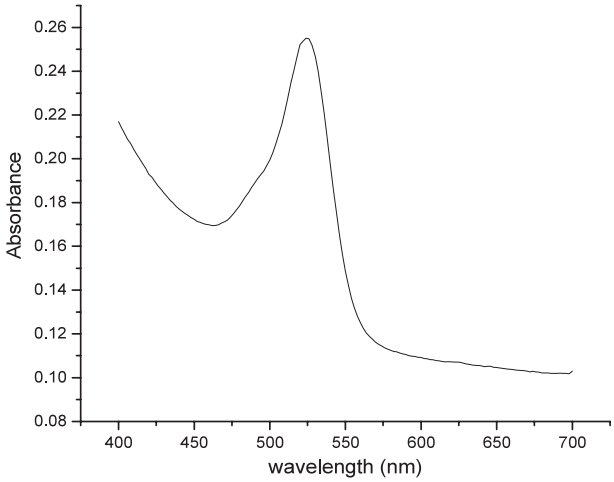

Figure 1. The absorption spectrum of Rh6G doped PMMA bulk sample.

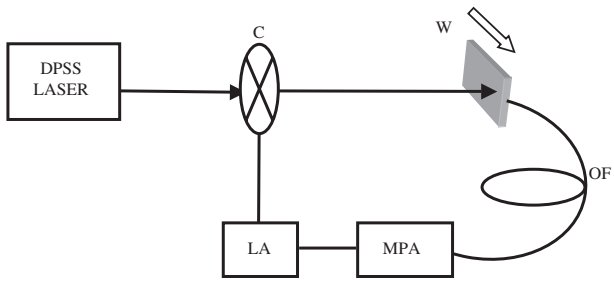

Figure 2. The experimental set-up used to record the fluorescence emitted from the side illuminated planar waveguide. C—chopper; W—waveguide; OF—optical fibre; LA—lock-in amplifier; MPA—monochromator–PMT assembly. The arrow shows the direction of translation of the waveguide.

waveguide structures. The reasons for choosing PMMA as the base material are its good optical quality and its compatibility with most of the organic dyes to be used as dopants. The well mixed monomer–initiator–dye mixture—the concentration of the dye in monomer being 1×10^{-4} M—was taken in a conical flask and evenly heated to 90 °C for 30 min until the solution became viscous. The viscous solution was allowed to flow freely along the surface of a clear glass plate at room temperature and was kept for 24 h in a dust free environment. Free standing film thus obtained was lapped and polished respectively with silicon carbide and alumina powder. The thickness of the sample was found to be 420 μm and essentially it is a two-dimensional waveguide.

To select the pump beam for exciting the dye doped waveguide, we recorded the absorption spectrum of the bulk sample using a spectrophotometer (JASCO UV/VIS/NIR V-570). In view of the absorption spectrum (figure 1), radiation at 532 nm (beam spot size $\sim$ 1.5 mm) from a diode pumped solid state (DPSS) laser (Nd:YVO_4) was used as the pump source. A schematic diagram of the experimental set-up is shown in figure 2.

The film waveguide was mounted normally on a translation stage with respect to the incident radiation. The side illumination of the dye doped waveguide generates fluorescence emission. The light emission from one end of the waveguide was collected by an optical fibre leading to a monochromator–photomultiplier tube assembly coupled with a lock-in amplifier (Stanford Research Systems SR850), for signal analysis. To measure the transmitted fluorescence as a function of propagation distance through the waveguide, the illumination point on the waveguide was varied by translating the waveguide horizontally across the laser source. The direction of translation is indicated by the arrow mark in figure 2. At each point of illumination, the fluorescence spectrum was charted. The experiment was repeated for three different pump powers, namely 0.9, 3.06, 9.28 mW. It was ensured that the sample was not damaged even at the highest pump power.

3. Results and discussion

The side illumination fluorescence spectrum was recorded for various propagation distances from one edge of the waveguide. Figure 3 shows the spectra of transmitted fluorescence light measured as a function of the propagation distance through the waveguide. As the propagation distance increases, the magnitude of the output intensity decreases due to loss mechanisms such as absorption and scattering. In addition, there is a red-shift for the peak fluorescence emission as the illumination distance from one edge of the waveguide is increased. A similar red-shift in the fluorescence emission from side illuminated dye doped fibre has also been observed by other workers [10, 11].

The red-shift of the fluorescence signal is produced by the self-absorption of the dye due to the overlapping of the absorption and fluorescence spectra of Rh6G [12]. As the fluorescence light is guided through the dye doped waveguide, the effective path length is increased resulting in self-absorption and re-emission causing a red-shift in the observed spectrum. The further the point of illumination from the observation end, the larger the effective path length, which results in increased interaction between the dye molecules and the enhanced fluorescence emission generated. This results in an increased self-absorption of the fluorescence and thereby shifting of the emitted fluorescence peak towards the red side.

Figure 4 shows the variation of the fluorescence peak wavelength as a function of propagation distance through the waveguide. For shorter propagation distances in the waveguide, the red-shift shows a linear behaviour, whereas at longer distances, the shift tends to exhibit a saturation behaviour. This mechanism is similar to the concentration dependent red-shift which is observed in dye solutions [13].

The fluorescence collected from the dye doped waveguide has a spectral width of about 100 nm and hence can be used as a broad wavelength light source for measuring the attenuation in the waveguide. The transmitted fluorescence is measured as a function of the propagation distance so as to characterize the attenuation in the waveguide.

From Beer–Lambert's law for linear optical attenuation in a medium,

$$I(\lambda, z) = I_0(\lambda) \exp(-\alpha(\lambda) z) \qquad (1)$$

where $I(\lambda, z)$ and $I_0(\lambda)$ represent the intensity of the transmitted light at wavelength λ at propagation distances z and $z = 0$ respectively and $\alpha(\lambda)$ is the linear attenuation coefficient corresponding to wavelength λ.

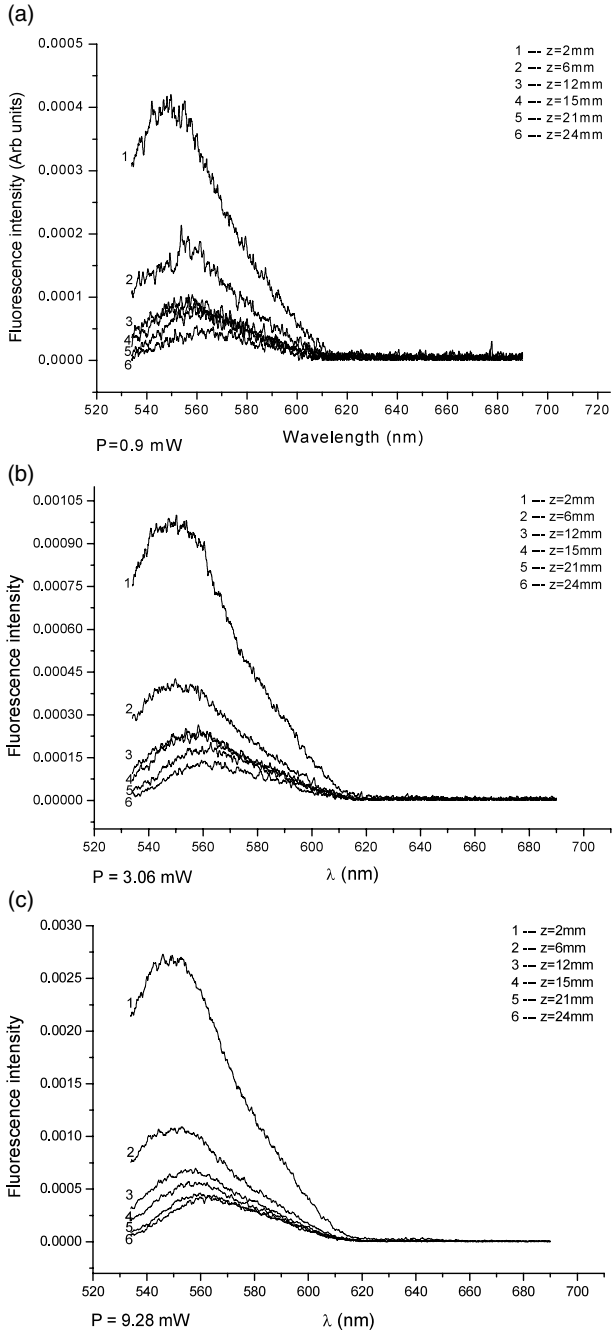

Figure 3. Transmitted fluorescence as a function of propagation distance through the waveguide.

We first applied Beer–Lambert's law to our data so as to characterize the optical loss in the waveguide. Figure 5 shows plots of the natural logarithm of the transmitted fluorescence intensity versus the propagation distance (data obtained from figure 3) corresponding to various emission wavelengths. An interesting observation is the nonlinear behaviour of these plots, which suggests that the loss coefficient is not a constant for the total length of propagation through the waveguide.

The nonlinear plot of $\ln I$ versus z can be fitted to a minimum number of straight lines (the method is known as peeling the curve) which will provide the values of loss

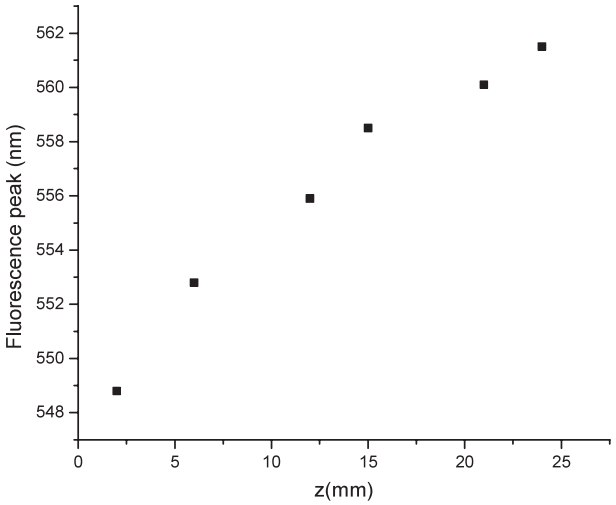

Figure 4. The variation of the fluorescence peak with propagation distance.

coefficients in the respective ranges of the waveguide length. Figure 6 shows the application of this method to the semilog plot at 600 nm.

For the lowest pump power, the plot can be fitted to two straight lines, whereas for higher powers it has to be fitted to three straight lines. This clearly suggests that as the light propagates through the waveguide, there arise some mechanisms which tend to alter the optical attenuation inside the waveguide. The general tendency is that the attenuation decreases for longer distances of propagation. One of the possible mechanisms of this behaviour is re-absorption of fluorescence light on the shorter wavelength side and subsequent emission in the larger wavelength region. This also supports the observation that this type of behaviour is more prominent in the longer wavelength region of the fluorescence spectrum. As the pump power is increased, the intensity of the fluorescence emission is also enhanced, which in turn causes increased probability of a re-absorption–emission process. This is exhibited as more than two linear parts in the $\ln I$–z plots corresponding to higher pump powers.

As the fluorescence light propagates through the waveguide, re-absorption and re-emission of light by the dye molecules take place. The re-absorption is on the shorter wavelength side of the fluorescence emission while the re-emission is in the longer wavelength region. It should also be noted that there is a red-shift in the fluorescence spectrum as the propagation distance increases. Hence the contribution from re-absorption–re-emission phenomena will lower the attenuation for longer wavelengths at the larger distances.

We also plotted the $\ln(I)$ versus $\ln(z)$ graph for the three pump powers (figure 7) to see the nature of the power law variation (i.e., $I(z) \sim z^{-n}$) in the fluorescence emission with respect to propagation distance.

The values of n are identical for all wavelengths in the shorter length region of the waveguide. The extents of such length regions in the waveguide exhibiting identical n values increase with the pump power, as is clear from figures 7(a) to (c). Thus such graphs show the extent in the waveguide region to which the intensity variation with z depends on an identical exponent. Additional experiments

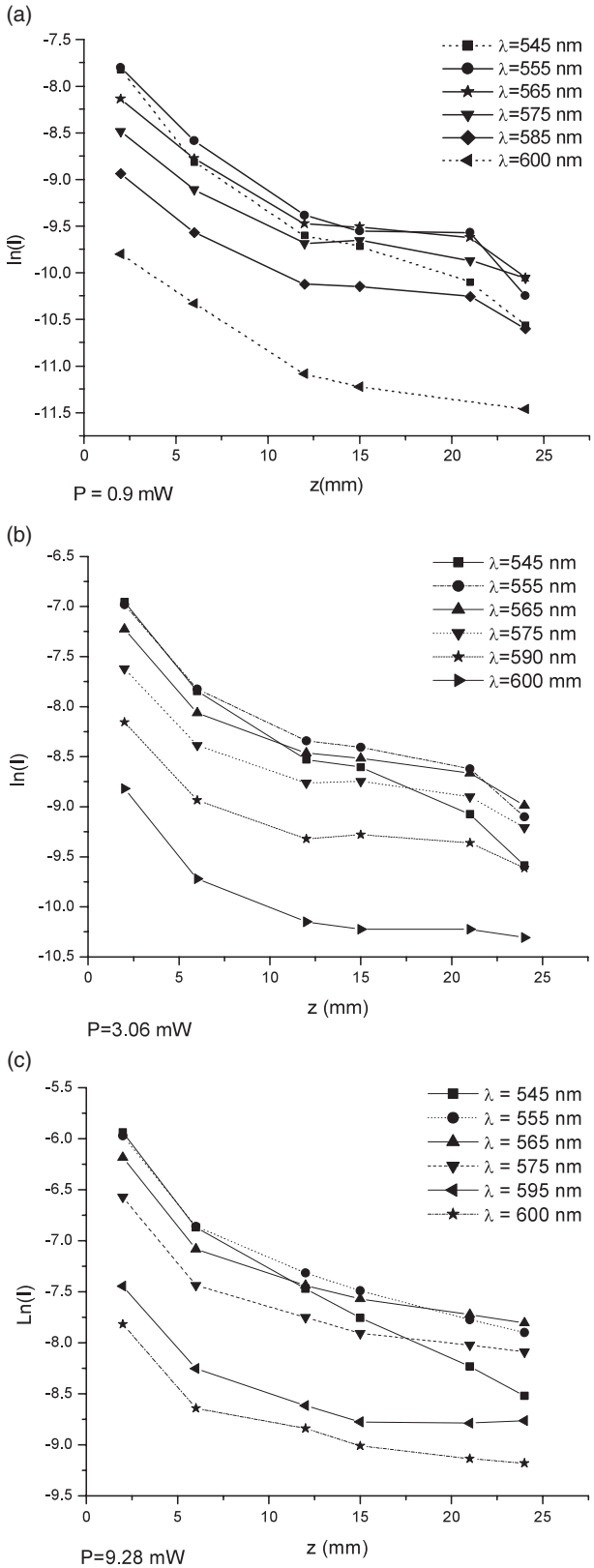

Figure 5. Plot of $\ln(I)$ versus z (z is the propagation distance through the waveguide).

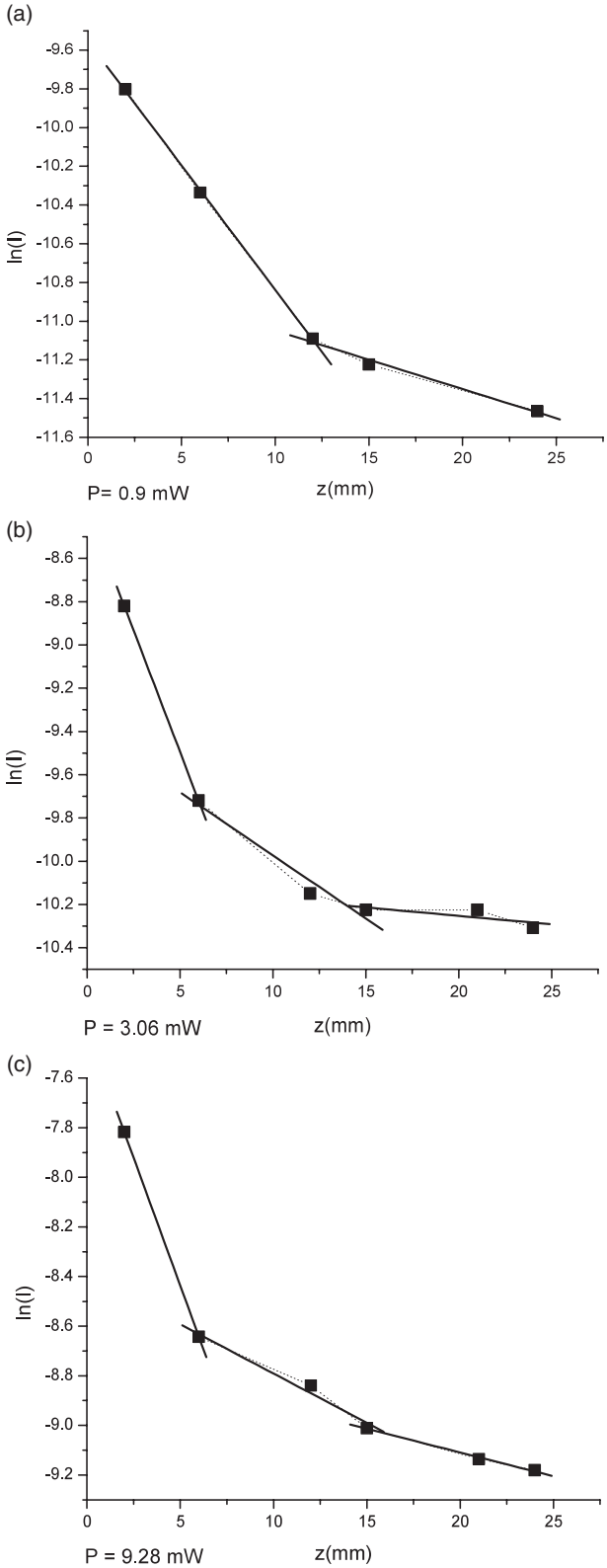

Figure 6. The 'peeling the curve' method applied to $\ln(I)$ versus z plot at $\lambda = 600$ nm. The solid lines represent the linear fits to the data.

are in progress to study the optical attenuation in polymer waveguides with different dye concentrations and thickness and the results will be reported elsewhere.

4. Conclusions

Using a side illumination technique, position-dependent tuning of light emitted from a rhodamine 6G doped planar waveguide

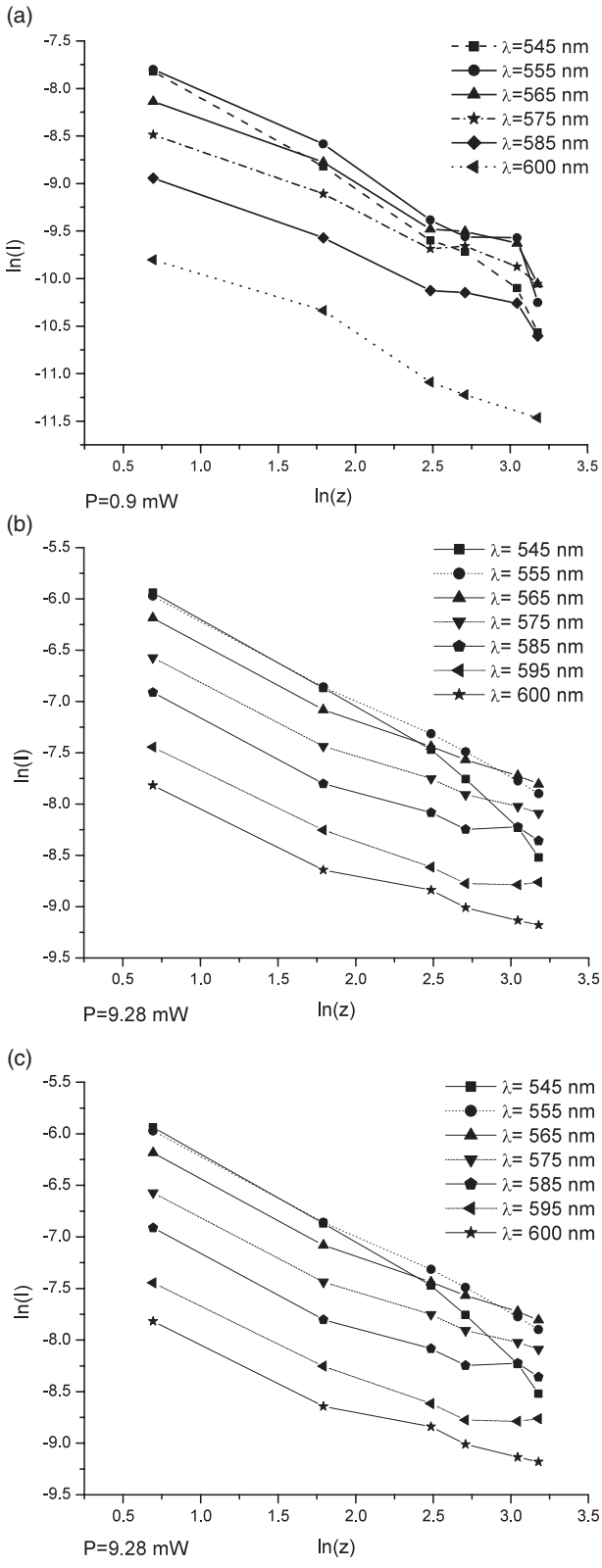

Figure 7. $\ln(I)$ versus $\ln(z)$ plots.

structure is observed. This is a potential method for getting tunable output from a waveguide laser. The data from the fluorescence collected from the waveguide are used to characterize the loss mechanisms in the waveguide. It has been observed that at longer wavelengths, there is a lowering of attenuation towards larger distances of propagation in the waveguides. This suggests that appropriate design of the waveguide will lead to a gain on the longer wavelength side.

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