High NA POF Dependence of Bandwidth on Fibre Length

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ABSTRACT

This paper presents experimental and theoretical results that help understand the behaviour of bandwidth in step index plastic optical fibres (SI-POF). The measurements of bandwidth and far field power distribution were analysed using models that relate bandwidth to the fibre exit numerical aperture. To explain the experimental results, it was found necessary to introduce modal interactions into the basic ray theory and, for this, a theoretical approach has been proposed.

I. INTRODUCTION

In practical plastic optical fibres (POF) links, the use of efficient optical sources may not attain over-filled launch conditions and as a consequence equilibrium mode distribution (EMD) may not be reached with the customary link lengths (less than 100m). Thus, bandwidth predictions obtained with models based on assumed launch conditions do not agree with experimental measurements unless launching is performed under very carefully designed laboratory conditions. The main goal of our paper therefore, is to show experimental and theoretical results about the behaviour of bandwidth in high NA step index POF links. The belief is that a better understanding of the factors that affect the fibre bandwidth will prove very useful in increasing the bandwidth of POF links in real situations.

We measured bandwidth in the frequency domain against fibre length for POFs with a numerical aperture (NA) of 0.5. We tested bandwidth under three conditions: without any scrambler, with a corrugated scrambler near the emitter, and with the same scrambler near the detector. We also measured the far field pattern (FFP) under the same conditions and estimated the exit NA of the fibre.

We studied the relationship between the measured bandwidth and the exit NA following reported models [1, 2]. Then, we modified the model to take into account the effect of the scrambler and to achieve a better fit to the measured data. Additionally, these results have been used to adopt a model based on ray theory, but also incorporating statistically varying scattering [3].

II. METHODS

We used a step-index fibre from Toray (PMMA core, 1mm -diameter,) type PGU-CD1001-22E. It is an upper-grade fibre with a numerical aperture of 0.5 and a relatively low attenuation (0.15dB/m). All fibre ends were prepared using the same standard cut and peel tools.

A. Description of the corrugated scrambler

The scrambler used in our measurements is shown in Fig. 1 and has been described previously [4]. The scrambler has seven fixed corrugations with a pitch of 6mm, and a depth of corrugation of 0.5mm. This scrambler has been reported to achieve the same constant exit NA irrespective of the values of the higher input NA. An important advantage of this scrambler is its easy use, by just attaching it to the fibre without damaging or modifying the POF link. In the measurements, the scrambler was always placed at the same end of the fibre, and from which we cut the various fibre lengths.

B. Experimental system to obtain fibre bandwidth

Bandwidth was measured directly in the frequency domain using a computer controlled system, which consists of a synthesised sweeper HP-83751A operating in the 10 MHz to 810 MHz frequency range, a scalar network analyser HP-8757D and a microwave power detector. The optical source was an AlGaInP laser diode emitting a maximum of 5mW at 645nm and with a typical divergence of 30º in the perpendicular plane, and of 7.5º in the parallel plane. The receiver incorporated a 1mm diameter high-speed silicon photodiode. Optical bandwidth was defined as the frequency at which the transfer function was 6dB (electrical) below its value at 10MHz. We first took measurements without the

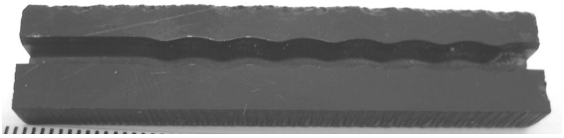

Fig. 1. Corrugated scrambler used in the measurements.

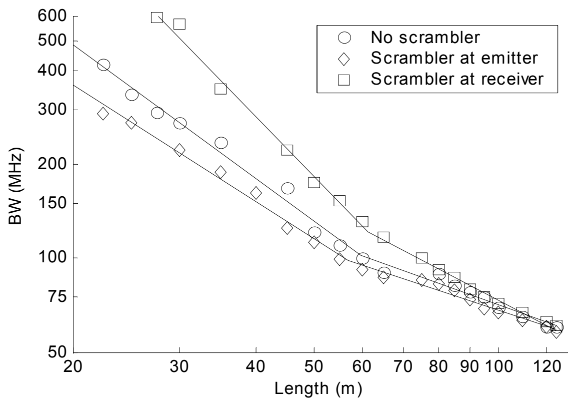

Fig. 2. Measured bandwidth as function of fibre length.

scrambler and then, we tested the influence of scrambling by taking measurements with the scrambler connected at the emitter side and then, by interchanging the fibre ends, the scrambler was at the receiver side. Subsequently, a given length (2.5 – 5 m) of fibre was cut from the end last used with the scrambler, and the whole procedure was repeated, until the system bandwidth limit was reached.

C. Set-up for far-field image acquisition

Immediately after the bandwidth measurement, the far field pattern (FFP) was acquired by imaging the fibre light output pattern (created on a semitransparent screen placed 7.5 cm from the fibre end), on a CCD camera (EDC1000). We processed these images to determine their centroids and the mean profile of the FFP. Then, the exit NA was determined from the sine of the semi-angle at which the intensity of the pattern reduced to 5 % of the maximum intensity at the centre.

III. RESULTS

For a high NA SI-POF, we have obtained bandwidth and exit NA as a function of fibre length under three conditions: (a) without scrambler, (b) with the scrambler near the emitter and (c) with the scrambler near the receiver.

A. Bandwidth versus fibre length

The results are shown in Fig. 2 using log-log coordinates. For long fibre lengths (above 80m), the bandwidth is similar for all conditions but the differences are noticeable for shorter lengths. In fact, when the scrambler is near the receiver the bandwidth is always greater than without the scrambler, while when the scrambler is near the emitter, the bandwidth is seemingly reduced. It has been reported [5], that for low NA launching, a scrambler near the emitter leads to higher exit NA and hence, to lower bandwidth.

By inspecting the results, it is possible to accept two different regions. For short lengths (up to 60m, say), bandwidth decreases more steeply with L than for longer lengths (longer than 60m). Thus, two straight lines of different slopes have been fitted to our data for each condition. Both straight lines minimise jointly the mean square error. In this way, the dependence of BW with length is fitted as:

$$BW = \begin{cases} C_1 L^{\gamma_1}\text{, if } L \le L_t \\ C_2 L^{\gamma_2}\text{, if } L > L_t \end{cases} \qquad (1)$$

where γ_1 and γ_2 parameters are the so-called concatenation factor of fibre. C_1 and C_2 have the meaning of the bandwidth of one meter of fibre. L_t is the fibre length at the intersection of the two lines calculated from the fits. Note that L_t is not a free parameter of the model.

The values of these parameters are shown in Table I for the three conditions.

TABLE I

Estimated fitting parameters and intersection length (L_t).

Parameter	No Scrambler	Scrambler at emitter	Scrambler at receiver
L_t (m)	59.6	56.7	61.3
γ_1	-1.42	-1.24	-2.01
C_1 (GHz)	34.5	14.6	477.7
γ_2	-0.70	-0.65	-1.01
C_2 (GHz)	1.8	1.4	7.9

B. Exit NA versus fibre length

The experimental NA obtained from the far-field patterns as described above is plotted in Fig. 3 as a function of POF length for all three conditions.

Exit NA increases with length for short distances, tends to stabilize at about 60 m and seems to slightly decrease beyond 60m. When the scrambler is near the emitter, the behaviour is the same than without scrambler but with a higher starting value. When the scrambler is near the receiver, the measurements are very noisy, but they are significantly lower than the others.

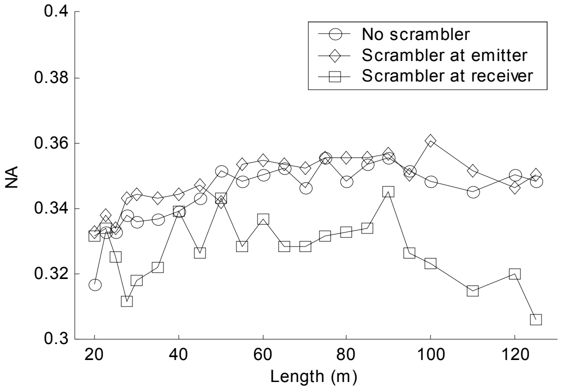

Fig. 3. Measured numerical aperture as function of fibre length.

IV. DISCUSSION

A. POF Bandwidth versus fibre length

For high NA SI-POFs illuminated by conventional commercial laser sources, we found a dependence of bandwidth with length, which is steeper than the basic ray theory prediction. In fact, we found two distinct regions in the log-log plot of bandwidth versus length, above and below a fibre length which is about 60m. For shorter fibre lengths, bandwidth decreases with length more steeply than for longer fibres. We think that this dependence is related to the different phenomena underlying light propagation inside the fibre. For short lengths, the dominant effect is modal dispersion caused by strong scattering in PMMA [6]. Thus, the power in more confined (inner) modes is transferred to the peripheral (outer) modes [7]. For longer lengths, however, the dominant effect is mode mixing and differential mode attenuation, this, being higher for the external (outer) modes. The intersection length, whose values are given in Table 1, is the length where the two effects are compensated (balanced), but we do not think this fact implies that the EMD has been reached. Therefore, we assume that after launching the modal distribution is spread with distance and instead of filtering out the slower (outer) modes with propagation, power is transferred to them, which is the reason why the concatenation factor is greater than one for short fibre lengths. Then, when the power is widely distributed among the modes, the differential mode attenuation and mode mixing become more noticeable. Thus, for longer fibre lengths the concatenation factor can be less than one.

We can expect an asymptotical behaviour and therefore, for longer lengths that those we measured, a third region should be present after the EMD is reached and thus, even lower concatenation factors should be expected, such as 0.5 as reported in [8].

An important factor for bandwidth measurements is the way light is launched into the optical fibre. In our experiments we have used a source which gives an under-filled launch. We argue that this condition is closer to what will be implemented in actual POF links, because efficient sources used for POFs (edge-emitting LEDs, VCSELs and lasers) have per se a lower NA than the fibre. In over-filled conditions i.e. when the source NA is greater than the effective exit NA of the fibre, the concatenation factors can be even less that 0.6 since modal dispersion should be negligible compared to differential mode attenuation and mode mixing.

B. Scrambler behaviour

A scrambler is a device that re-distributes the power among the modes and filters out those modes less confined. The predominant effect depends on the input mode distribution and when this is very narrow, the scrambler spreads the power from inner to outer modes, actually scrambling them. When the input mode distribution is wide, then the dominant effect is the localised filtering out of weakly guided modes.

In our experiments with the scrambler close to the emitter, the relatively narrow power distribution launched by the laser is quickly spread. Thus, the emitter closely followed by the scrambler is equivalent to a wider launching distribution. In such a case, dispersion in the fibre is low relative to differential mode attenuation, and thus, the concatenation factor for this condition is lower than that of the fibre without scrambler. Also, the bandwidth is lower than without the scrambler, because the higher modes introduced at shorter lengths have more time delay relative to the condition without the scrambler and for which these modes are not present from the beginning.

On the other hand, when the scrambler is just before the receiver, it acts as a localised mode stripper. Since the less confined modes that are filtered out by the scrambler are those with a greater time delay, bandwidth is enhanced. This enhancement (50% for 50m) is comparable to that reported in [2]. We hypothesise that higher concatenation factors are obtained because modal dispersion becomes more evident since peripheral modes, which suffer from higher mixing and attenuation, are stripped out by the scrambler. These later modes would contribute to a lower concatenation factor if the scrambler were not used.

The exit NA obtained from the far field patterns is in good agreement with our hypothesis about the changes in the modal distribution. The measured exit NA suggests that essentially outer modes are slower as assumed by ray theory, and their filtering out improves the bandwidth.

C. Relationship between bandwidth and exit NA

To explain the bandwidth dependence with fibre length, we have used a model based on the experimental determination of the exit NA of the fibre to predict its bandwidth [1, 2]. The equation relating exit NA and bandwidth is the following:

$$BW = \frac{2n_c c}{NA^2 L} \tag{2}$$

where n_c is the core refractive index (1.49), c is the light speed in vacuum and NA is the exit NA which is a function of length (L). Note that in [1, 2] the exit NA was determined from the sine of the angle at Half-Width-Half-Maximum (HWHM). In this work, exit NA is defined as the sine of the semi-angle at which the intensity is reduced to 5%.

In Fig. 4 experimental results are plotted along the prediction of this model as a continuous line. One can see that the model represents quite well the data without the scrambler but at short lengths, the model overestimates

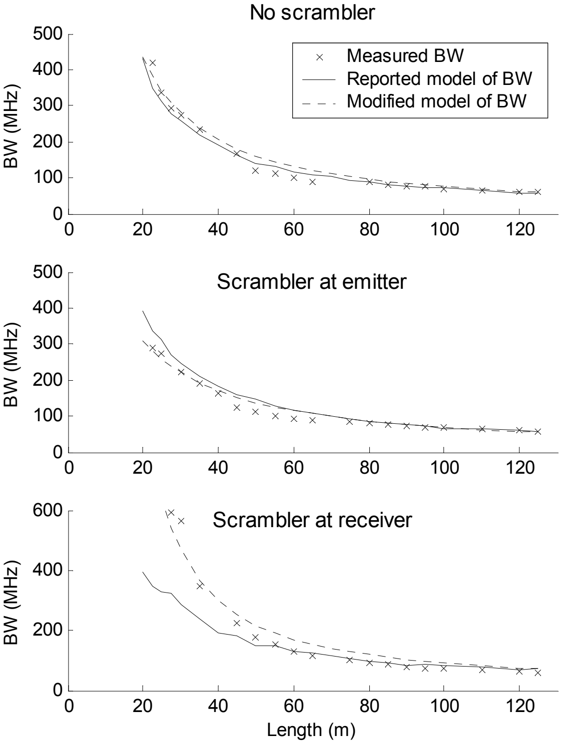

Fig. 4. Bandwidth versus fibre length. Experimental data and predictions from the models based on the measured exit NA.

the bandwidth when the scrambler is at the emitter end and underestimates the bandwidth when the scrambler is at the receiver side. We think that the problem is that this model does not take into account the history of the ray paths before they reach the fibre end. If we have into account how the slower ray path changes with length we can estimate bandwidth as

$$BW = \frac{c}{n_c \int_0^L \left(\frac{1}{\cos\theta} - 1 \right) dL} \tag{3}$$

where θ is the ray angle with fibre axis for the slower ray (effective critical angle) obtained from the measured exit NA by: $\sin\theta = NA/n_c$, and supposing $NA \ll n_c$, bandwidth can be approximated as

$$BW = \frac{2 n_c c}{K + \int_{L_0}^{L} NA^2 \, dL} \tag{4}$$

where L_0 is the shorter length for which the NA was measured and K is a parameter that accounts for the integral up to L_0. For the scrambler at the receiver only more confined modes reach the receiver. In this case the contribution to the integral of the only modes that the receiver sees is very small. In fact, it can be thought as very narrow initial mode distribution. The K parameter that was fitted to the measured data was 2, 2.8 and 0.8 for the fibre without scrambler, with scrambler at emitter and with scrambler at receiver respectively. These fits are shown in Fig. 4 as a dashed line exhibiting a better agreement at short lengths when the scrambler is used.

V. CONCLUSION

Our results show significant bandwidth enhancement of about 108%, 45% and 2% for 30m, 50m, and 90m respectively when the scrambler is placed near the receiver. In contrast, there is a decrease in bandwidth when the scrambler is placed near the emitter. This last finding suggests that with the use of wide angle input sources (wider than EMD) that might also help to reach EMD, the bandwidth decreases more noticeably at shorter link lengths, and therefore, should have no practical advantage. Overall, the present results confirm that the 7-corrugation scrambling device represents a simple and effective way of significantly increasing the bandwidth of a high NA POF link, when this is attached to the receiver end. In the present measurements, with low NA launch, it was also observed that the percentage increase in bandwidth reduces with increasing link length.

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