PROPAGATION PROPERTIES OF STRESSED POFS

M. A. Losada, J. Mateo, I. Garcés, I. Salinas, J. Zubía (2)
CPS, Universidad de Zaragoza, C/ María de Luna 1, 50018 Spain
(alosada@posta.unizar.es)
(2) Universidad del País Vasco, Spain

Abstract: *We found that extensive long-duration bending of plastic optical fibres produces a permanent change in their mode coupling properties. In fact, these stressed fibres show stronger mode coupling than unstressed fibres of the same types. Thus, in this paper, we have investigated how the attenuation and bandwidth of PMMA plastic optical fibres are altered after bending stress.*

1. Introduction

Plastic optical fibres (POF) are considered nowadays as a suitable media for high-performance fibre links at very short distances [1]. In particular, POF technology is recently attracting high interest in data transmission for local area networks (LANs) such as those for office, home or automobile applications [2]. However, when installing an optical-fibre-based link in a house or a car, the cable has to be repeatedly bent, thus increasing radiation losses [3]. Curvature losses for plastic optical fibres of the same material polymethyl-metacrylate (PMMA), but different numerical aperture (NA) and attenuation were measured for a number of configurations, showing that those fibres with a stronger mode coupling have more curvature losses, nearly independent on their numerical aperture [4]. On the other hand, we found evidence of changes in the mode coupling behaviour for curved fibres that can become permanent if the fibres are bent for a long time [5]. In fact, fibres subjected to bending stress show an increase in their coupling strength similar to that found for silica fibres under mechanical stretching and high temperature [6]. From now on, we will call the fibres whose coupling properties have changed due to extensive long-duration bending, stressed fibres.

Therefore, in this paper, we set out to explore the behaviour of stressed PMMA POFs. We compare here the attenuation and bandwidth of stressed fibres with those of unstressed fibres, as well as the effect of curvature scrambling on both properties. It is well known that the state of mode coupling affects the information carrying properties of the fibre. For instance, in step-index POFs, a higher mode coupling can decrease the effects of mode dispersion, reducing the broadening of transmitted pulses for distances higher than the coupling length for which the equilibrium mode distribution is reached [7]. Our results obtained using a frequency domain system are consistent with an increase of power transfer from low to high order modes in curved fibres.

2. Methods

We measured several PMMA plastic optical fibres from Toray with a 1mm-diameter core and step-index profile: PGU-CD1001-22E (PGU), PFU-CD1001-22E (PFU) and PMU-CD1002-22-E (PMU). The first two are upper-grade fibres with a relatively high numerical aperture of 0.5 and 0.46, respectively, but a relatively low attenuation (0.15dB/m). The PMU fibre has a low NA of 0.32. In addition, a HFBR-RUS500 fibre (HFBR) from HEWLET-PACKARD with a numerical aperture of 0.47 was also tested. Segments of the fibres were subjected to bending stress and tested to obtain their mode coupling properties. In addition, the attenuation and bandwidth of stressed and unstressed PFU fibres were measured. The experimental systems used to obtain these parameters are described below.

2.1 Bending stress

The set-up designed to induce permanent changes in the coupling properties of the fibres by bending stress consisted on 12 posts of 1cm diameter screwed to an optical table with a 3x4 configuration. The distance between posts was of 10cm in both dimensions. The fibre was rolled in quarters of a turn over each post as shown in Figure 1.

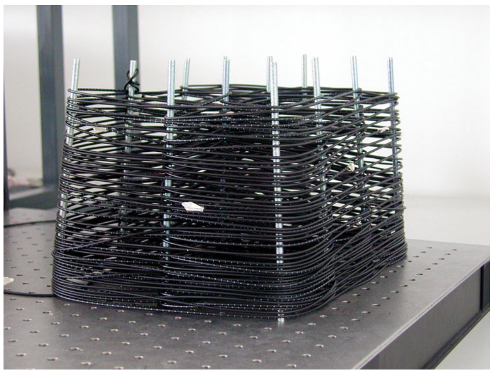

Figure 1: Arrangement to produce bending stress.

2.2 Mode coupling

The experimental set-up to measure the mode coupling properties was explained with detail elsewhere [5]. A He-Ne laser (633nm) was launched directly into the front end of the fibre, which was mounted onto a rotating stage to allow input-angle variation. Figure 2 shows this experimental set-up. The output intensity images were processed to obtain the launch angle for which the output pattern changes from disk to ring, known as the transition angle. Once the angle scan was completed, a length of the fibre was cut from the further end, and the whole

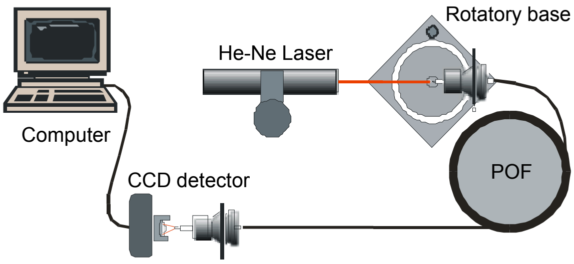

Figure 2: Mode coupling experimental set-up.

procedure was repeated. Then, we followed Gloge's power flow equation to derive a log-log relation between transition angle (θ_t) and fibre length (z) in order to obtain the mode conversion coefficient *D* by fitting a log-log plot of the data with a straight line [6].

2.3 Attenuation and bandwidth

Bandwidth was measured directly in the frequency domain using a computer controlled scalar network analyser HP-8757D. The transmitter source was a laser diode emitting at 650nm. The receptor was based on a 1mm^2 area high-speed silicon photodiode followed by an amplifier. A given length of fibre was rolled on an 18cm diameter reel to avoid spurious bending.

The input-output power ratio was obtained from 10MHz to 810MHz using a synthesised sweeper HP83752A. The transfer properties of the system were accounted for by a reference, a 10cm length of connectorised fibre. Optical bandwidth was defined as the frequency for which the transfer function was 6dB$_e$ below its value at 10MHz. Optical attenuation was calculated from the value of the transfer function at 10MHz. Then, we tested the influence of scrambling by rolling 1.5 meters of the fibre (5 turns) onto a scrambler which consisted of two 2.5cm diameter mandrels separated 5cm. The power loss and bandwidth was measured first with the scrambler connected at the transmitter and then, with the scrambler connected at the receptor. Finally, a given length of fibre (2.5-5 meters) was cut from the extreme with the scrambler, and the whole procedure was repeated.

3. Results

3.1 Effects of bending stress on mode coupling

Figure 3 shows the transition angle for the PGU and PFU fibres as a function of fibre length in log-log coordinates. In the figure the stressed and unstressed fibres can be compared. Linear fits to Gloge's model are also shown. In Table 1, the parameters for the linear fits are given for all fibres tested.

For the unstressed fibres, a linear fit with a slope near 0.5 was always found, indicating that Gloge's model is followed. The log-log plots of stressed POFs, however, do not follow Gloge's model, showing much

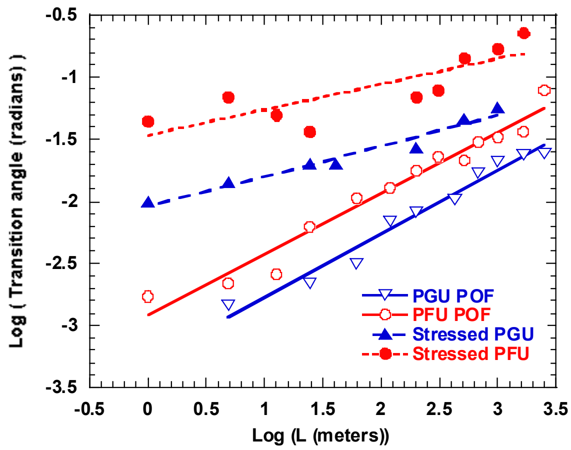

Figure 3: Mode coupling for stressed and unstressed POFs.

shallower slopes than those found for the unstressed fibres. This flattening indicates that the stressed fibres have a power output distribution nearly independent of the input angle even for short fibre lengths. Thus, the values of the mode conversion coefficient D are more than one order of magnitude higher than those found under unstressed conditions. A similar effect was found when the transition angle versus fibre length was measured in fibres with curvatures near the input end. The output power pattern of short segments of these fibres revealed a higher numerical aperture when curved, indicating that the effect of bending is to equalise the mode power distribution in a short distance. The fibres curved for a short time (less than 30 minutes) recover their initial values when unbent, while in the stressed fibres the changes in mode coupling behaviour are permanent. The effects of bending stress are the same for all fibre types, and even in these conditions standard high NA fibres (HFBR) still show significantly stronger coupling than the other types.

3.2 Effects of bending stress on bandwidth and attenuation

The procedure described in section 2.3 was applied to 100 meters of unstressed PFU fibre. Then, another 90 meters of the same fibre were arranged as shown in Figure 1 for 72 hours. Right after releasing the fibre from the bending set-up, it was rolled on the 18cm reel and its bandwidth and attenuation were obtained.

Table 1: Gloge's model fitting parameters.

FIBRE		SLOPE	D
PFU	Unstressed	0.49	7.310^{-4}
	Stressed	0.20	0.0132
PGU	Unstressed	0.51	3.510^{-4}
	Stressed	0.24	0.0043
PMU	Unstressed	0.52	2.610^{-4}
	Stressed	0.23	0.0054
HFBR	Unstressed	0.49	9.810^{-4}
	Stressed	0.11	0.0227

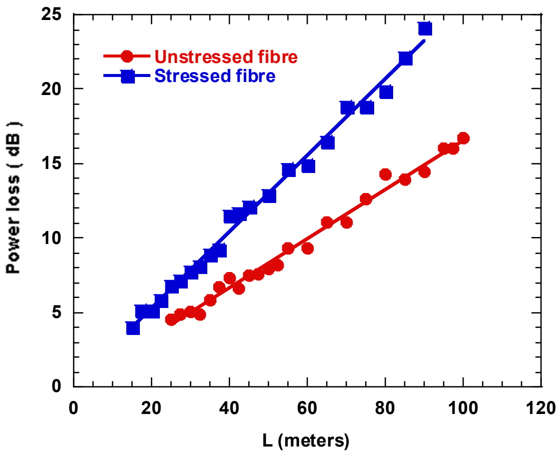

Figure 4: Attenuation in dB versus distance.

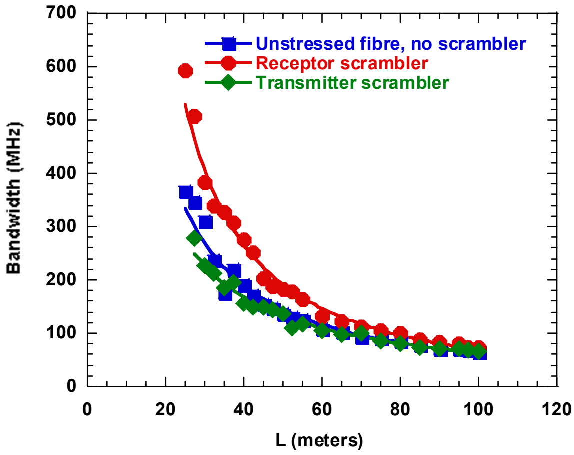

Figure 6: Bandwidth for the unstressed fibre.

The results are plotted in Figures 4 (attenuation) and 5 (bandwidth) as a function of fibre length along with linear and power fits respectively.

We found that higher attenuation for the stressed fibre: 0.25dB/m compared to 0.16dB/m for the unstressed one. This is shown in Figure 4 by the different slopes of the lines showing the attenuation versus distance for the stressed and unstressed fibres. The intercepts are 0.04dB and 0.2dB for the stressed and unstressed fibres respectively. The bandwidth, however, remains unaltered by bending stress up to fibre lengths of 40 meters. For shorter lengths, the bandwidth for the unstressed fibre is significantly wider as shows Figure 5.

3.3 Influence of scrambling on bandwidth and attenuation

We tested the influence of scrambling on both parameters, finding marked differences in the behaviour under scrambling of the stressed and unstressed fibres. The effect of the scrambler on attenuation for the unstressed fibre is a small increment on the overall losses (a 0.4dB and a 0.5dB increase in the intercept when the scrambler is at the transmitter and receptor ends, respectively), which does not alter the slope. For the stressed fibre, however, the changes in attenuation with scrambling are more important. The value of the intercept when the scrambler is at the receptor end increases by 2.7dB, and there is also a change in the slope, which is now 0.23dB/m. The change when the scrambler is at the transmitter end is of 0.8dB.

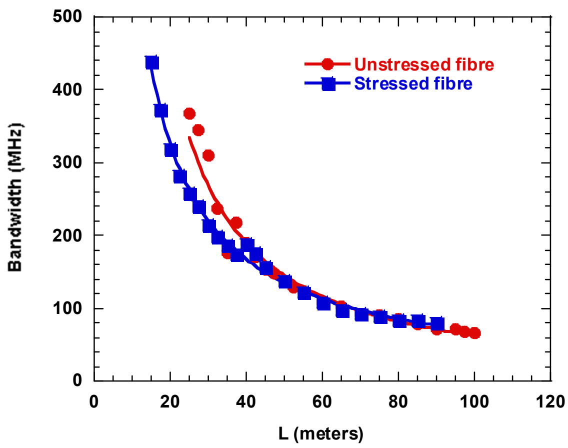

Figure 5: Bandwidth versus distance.

On the other hand, the bandwidth of the stressed fibre is unaffected by the scrambler, while the effect on the unstressed fibre is a dramatic bandwidth enhancement when the scrambler is placed at the receptor end. Moreover, a small decrease is found when the scrambler is at the transmitter end. In Figure 6, bandwidth for the unstressed PFU fibre is plotted for the three conditions.

4. Discussion

It has been shown that bending a plastic optical fibre increases the radiation losses and thus, diminishes its output power. It also increases power transfer between modes, which forces the equilibrium mode distribution in a shorter distance than for straight fibres. This later effect has two consequences: First, it makes the output power pattern more independent of the input source power distribution acting like a mode scrambler [8]. Second, strong mode coupling has been associated to a slower increase of pulse broadening with fibre length [9].

In this line, we found that the effects of scrambling in unstressed fibre bandwidths are consistent with an increase of power transfer from lower to higher order modes induced by curvatures. Thus, when the scrambler is right after the input end, the power initially launched to central modes is spread over a greater number of modes, narrowing the bandwidth. We found this decrease in bandwidth in our data, although the effect is very small because our source has a wide numerical aperture and distributes power in most modes (overfilled launch) and thus, the scrambler has little effect. When the scrambler is just before the output end, however, we found an important bandwidth enhancement. In this case, we argue that the effect of the scrambler is that of a mode filter. Power from higher order modes, with the longer delays is radiated, thus widening the bandwidth. As the distance from the scrambler to the detector is short, there is no time for new higher order modes to suffer further delay. The overall attenuation of the unstressed fibre with scrambler is only slightly increased, which implies that the filtering affects a small percentage of power. However, at least for receptor scrambling, this radiated power is in the most important modes regarding the bandwidth, which are those with the longer delays.

In addition, we report a permanent increase of mode coupling for fibres after long-duration bending stress. This enhancement of mode coupling can be explained by an increase of power transfer caused by macro-cracks similar to those formed by fibre ageing, whose origin can be macro-defects, curvatures, high pressures, etc as was proposed in a previous study [10]. We found that stressed fibres show also higher attenuation, which is consistent with this explanation. The radiation losses with the scrambler have a greater increase than for the unstressed fibre, which agrees with the relationship between mode coupling and curvature losses established in a previous study [5]. The effect of bending stress on bandwidth has been also assessed comparing bandwidths for stressed and unstressed fibres. We found that there is no significant difference at distances larger than 40 meters, suggesting that both fibres have a similar mode distribution for long distances. However, the intense power transfer from lower to higher order modes degrades the stressed fibre response at shorter distances. The fact that the scrambling has no effect on the bandwidth of the stressed fibre can be explained considering the increase of power losses when the scrambler is at the receptor end. From this fact, we can argue that there is a higher proportion of power in higher order modes, which suffer more the effect of radiation losses in the scrambler. This mode filtering is, however, insufficient to restore the bandwidth as it happens with the unstressed fibre.

5. Conclusions

We found that PMMA POFs bent with small curvatures for a long time, suffer a permanent reinforcement in their mode coupling. As a consequence, the stressed fibres show higher attenuation and have narrower bandwidths for distances below 40 meters. Although scrambler at the receptor end can improve the unstressed fibre bandwidth, it does not have much effect for the stressed fibre.

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