Analysis of Strained Plastic Optical Fibers

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***Abstract*—We found a permanent change in the mode coupling properties of plastic optical fibers (POFs), produced by extensive long-duration bending. In fact, these strained fibers show stronger mode coupling than unstrained fibers of the same types. Thus, we have investigated how propagation properties of POFs are altered after bending, finding an increase in attenuation for strained fibers. In addition, we found a bandwidth decrease for the strained fibers compared to the unstrained ones, more noticeable for fiber lengths shorter than 40 m.**

***Index Terms*—Bending losses, mode coupling, plastic optical fiber (POF).**

I. Introduction

PLASTIC OPTICAL fibers (POFs) are attracting high interest in data transmission for short distance communications. POFs are suitable candidates for office, home, or automobile applications, because of their low-cost installation and high flexibility compared to glass optical fibers of similar diameters. This higher flexibility of POFs is an advantage when installing an optical-fiber-based link in a house or a car, where the cable has to be repeatedly bent. This bending, however, increases radiation losses that have to be carefully assessed [1]. Curvature losses for POFs with different numerical aperture (NA) and attenuation for different configurations were measured in a previous work [2]. Results showed that those fibers with a stronger mode coupling have more curvature losses, nearly independent on their NA due to power transfer from lower to higher order modes [2]. In addition, we found an increase in mode coupling induced by bending strain, which can become permanent if the fibers are subjected to repeated bending or are bent for a long time [3]. This increase of mode coupling could be explained by microscopical changes similar to those induced by fiber aging, [4]. It is known that the state of mode coupling affects the information carrying properties of the fiber [5]–[7]. Therefore, in this letter, we call the fibers whose coupling properties have changed due to extensive long-duration bending strained fibers and compare their behavior with unstrained fibers of different characteristics and from different manufacturers. We assess the changes in mode coupling produced by strain, we show that strained fibers do not recover completely their original properties, and finally, we compare the attenuation and bandwidth of strained and unstrained fibers.

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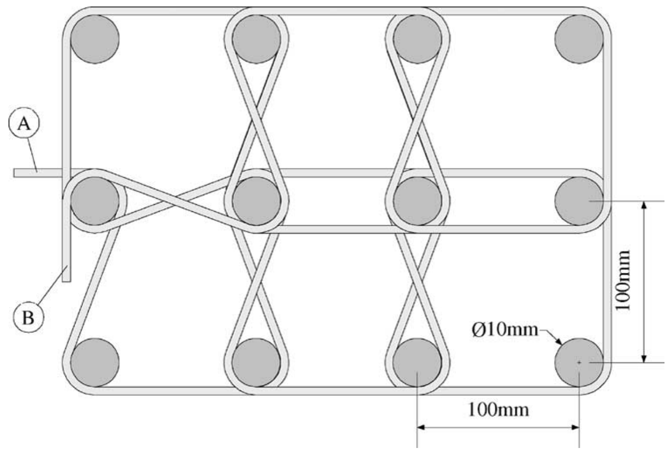

Fig. 1. Schematic representation of the experimental arrangement to produce bending strain. It shows the fiber path which was designed to have 90° turns in each post. This path starts in A and from B is repeated until the fiber end is reached.

II. Effect of Bending on Mode Coupling

We measured several commercial POFs from Toray and Hewlett-Packard. The fibers have step-index profile with a polymethyl methacrylate (refractive index of 1.49) core of 1-mm diameter. The commercial names of fibers from Toray are: PGU-CD1001–22E (PGU), PFU-CD1001–22E (PFU), and PMU-CD1002–22-E (PMU). The first two are upper-grade fibers with a relatively high NA of 0.5 and 0.46, respectively, but a relatively low attenuation (0.15 dB/m). The PMU fiber has a lower NA of 0.32. In addition, an HFBR-RUS500 fiber (HFBR) supplied by Hewlett-Packard with an NA of 0.47 was also tested. Segments of the fibers were subjected to distributed bending and tested to obtain their mode coupling properties while other segments were unaltered to compare their properties.

The setup built to induce homogenous bending strain was designed to have curvatures regularly distributed along the fiber length. It consisted on 12 posts of 1-cm diameter screwed to an optical table with a 3×4 configuration. The distance between posts was 10 cm in both directions. The fiber was rolled in quarters of a turn over each post as illustrated by the schematic in Fig. 1. The time that the fiber was in this setup and the time before measuring its properties was determined from the results described below in Section III.

The method used to estimate mode coupling strength is based on the changes in the fiber far field pattern (FFP) caused by mode coupling. The FFP is a disk for long fibers, independently of the launching angle. For shorter lengths, a disk is also found when light is launched at smaller angles, but if the launching angle increases, the FFP flattens until it looks like a ring, indicating a feeble mode coupling. The launching angle

TABLE I
SLOPE AND MODE CONVERSION COEFFICIENT (D) OBTAINED FROM THE LINEAR FITS TO DATA FOR STRAINED AND UNSTRAINED FIBERS

Fibre		Slope	D
PFU	Unstrained	0.49	7.3×10^{-4}
	Strained	0.20	1.3×10^{-2}
PGU	Unstrained	0.51	3.5×10^{-4}
	Strained	0.24	4.3×10^{-3}
PMU	Unstrained	0.52	2.6×10^{-4}
	Strained	0.23	5.4×10^{-3}
HFBR	Unstrained	0.49	9.8×10^{-4}
	Strained	0.11	2.3×10^{-2}

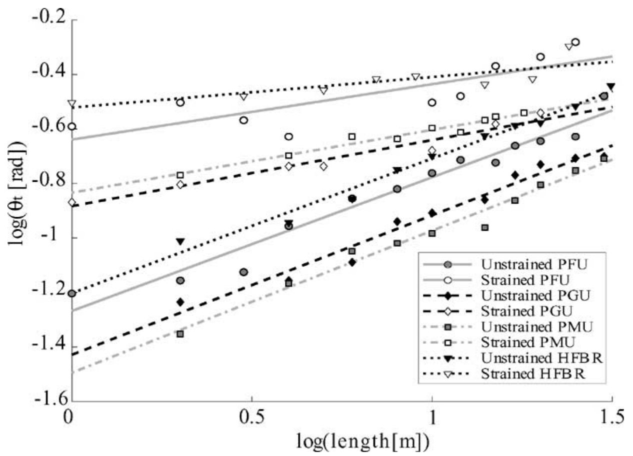

Fig. 2. Logarithmic plot of the transition angle in radians versus fiber length in meters for strained (open symbols) and unstrained (filled symbols) fibers.

for which the disk to ring transition occurs is known as the transition angle (θ_t) and is related to mode coupling strength, according to Gloge's model [8]. The procedure designed to obtain the transition angle is only briefly described here as it has been explained with detail elsewhere [2]. A He–Ne laser (633 nm) was launched directly into the fiber, which was mounted onto a rotating stage to allow input-angle variation. The FFP images were processed to estimate θ_t. Then, a given length of the fiber was cut and the whole procedure was repeated to obtain the variation of θ_t with fiber length. The relationship of θ_t and the mode conversion constant (D) was derived by Gloge as

$$\log(\theta_t) = \frac{1}{2}\log(z) + \log\left(2D^{1/2}\right). \tag{1}$$

Straight lines were fitted to the log-transformed data to assess if Gloge's model was followed. According to this model, the slopes should be of 0.5. In Table I, the fitting parameters are given for all fibers tested. In Fig. 2, data and fits are jointly represented showing the log–log plot of the transition angle as a function of fiber length.

For the unstrained fibers, all the linear fits exhibited a slope near 0.5, showing a good agreement with Gloge's model. However, strained POFs do not follow this model, showing much shallower slopes which make the values of D more than one order of magnitude higher than those found under unstrained conditions. The shallower slopes of strained fibers suggest that they have a FFP nearly independent of the input angle, because their stronger mode coupling induces power spreading among the different modes. These effects are found for all fiber types although both the change and the initial value of D are different for each type, presumably due to elasticity differences among the fibers.

TABLE II
TRANSITION ANGLE IN RADIANS MEASURED IN DIFFERENT RECOVERING TIMES FOR STRAINED FIBERS PFU AND PGU

	Transition Angle(rad)	
Fibre Condition	PFU fibre	PGU fibre
Unstrained	0.01	0.01
Strained for 24h		
- Just after releasing	0.27	0.35
- 24h after releasing	0.12	0.22
- 48h after releasing	0.12	0.19

III. Partial Recovery of Coupling Properties in Bent Fibers

We observed that when the studied POFs are bent for less than 30 min, their mode coupling does not increase [2]. However, with a 2-h-long strain, the transition angle increases if measured just after releasing the fiber. Then, if the fiber is left without strain for several hours, the transition angle decreases although the initial value is never reached. Therefore, it is important to assess when the changes in mode coupling produced by bending strain become stable. We quantify changes in mode coupling by measuring the variation in the transition angle for 3-m fibers, as it is at short fiber lengths where the effects of a feeble mode coupling are more evident. First, we measured the transition angle for the unstrained fibers, and these same segments were bent using the setup in Fig. 1 for 24 h. After the 24-h strain, the transition angle was obtained at three different times: first, just after releasing the fiber, 24 h after releasing, and finally, 24 h later. These experiments were performed for PFU and PGU fibers and the results are shown in Table II. The transition angle increases after the first rest interval and then, stabilizes in a value greater than the original one. Thus, we confirm that there is only a partial recovery of the original properties of fiber after bending strain. We found slight recovery differences which presumably depend on the flexibility and quality of the particular fiber, being the tested fibers from our experience, some of the best quality in the market.

IV. Effect of Bending on Bandwidth and Attenuation

Bandwidth was measured directly in the frequency domain using a computer-controlled system, which consist of a synthesized sweeper HP-83 751A operating in the 10–810-MHz frequency range, a scalar network analyzer HP-8757D, and microwave power detectors. The optical source was an AlGaInP laser diode emitting an optical power of 5 mW at 645 nm and with a typical divergence of 30° in the perpendicular direction, and of 7.5° in the parallel direction. The receiver was based on a 1-mm-diameter high-speed silicon photodiode. Attenuation and bandwidth measurements were taken by a differential method by using a fiber of 10-cm length as reference. This procedure was applied to 100 m of unstrained PFU fiber. Then, another 90 m of the same fiber were arranged, as shown in Fig. 1 for 24 h. Once the fiber was released, it was rolled on an 18-cm reel

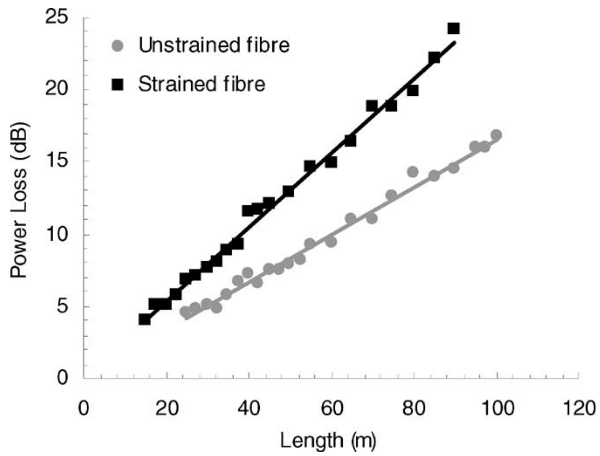

Fig. 3. Power loss in decibels versus fiber length for strained (squares) and unstrained (circles) for the PFU fiber.

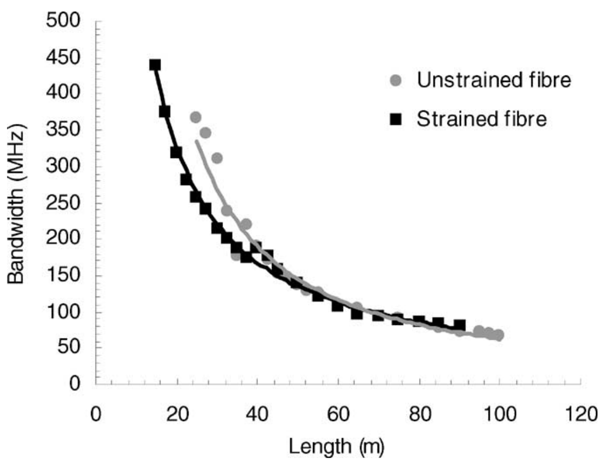

Fig. 4. Bandwidth in megahertz versus fiber length for strained (squares) and unstrained (circles) for the PFU fiber.

and, after 24 h, its bandwidth and attenuation were obtained. Attenuation and bandwidth results as a function of fiber length are plotted in Fig. 3 and in Fig. 4 along with linear and power fits, respectively.

From Fig. 3, we found higher attenuation for the strained fiber: 0.26 dB/m, compared to 0.16 dB/m for the unstrained one, which is consistent with an increase of unguided power due to microscopical fiber degradation. The bandwidth, however, remains unaltered by bending strain up to fiber lengths of 40 m. For shorter lengths, the bandwidth for the unstrained fiber is significantly wider as shows Fig. 4.

Results in Figs. 3 and 4 were obtained for a high NA fiber with a relative low NA source, where overfilled launching condition was not reached. To obtain a comparison of the bandwidth for strained and unstrained bandwidth under conditions approaching overfilled launch, we used a curvature scrambler near the emitter end of both fibers. In this condition, the bandwidth of strained fiber was unaltered but unstrained fiber bandwidth decreased at short lengths, giving a similar behavior to that of the strained fiber. We argue that the effect of the scrambler on the unstrained fiber is to spread the power initially launched to more confined modes over weakly guided modes, narrowing the bandwidth. These results suggest that under overfilled launch there are no significant differences in bandwidth for strained and unstrained fibers, even for the shortest lengths tested.

V. Summary and Conclusion

We have observed a permanent increase in the mode coupling for POFs after long-duration bending strain. This effect was found for all fibers tested. For fibers of upper quality (PFU and PGU), there is a certain recovery of their original properties after releasing although they do not reach the unstrained values again. We found that strained fibers exhibit higher attenuation than unstrained ones, which is consistent with a greater power transfer to higher or unguided modes that increases radiation throughout the fiber. Regarding bandwidth, we found that there is no significant difference at distances larger than 40 m, suggesting that both fibers have a similar mode distribution at these distances. However, at shorter lengths, the distributed-over-length power transfer from lower to higher order modes degrades the strained fiber bandwidth significantly in underfilled conditions. In conditions nearer to overfilled launch, strained and unstrained fiber bandwidths perform similarly, even at short lengths.

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