Transmission Performance of Plastic Optical Fibers Designed for Avionics Platforms

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***Abstract*—Plastic optical fibers (POFs) have been proposed and implemented in the avionics environment lately, and temperature is naturally a big factor that can affect their performance in those platforms. We present an experimental characterization of the transmission properties of POFs comparing the performance of standard fibers with that of fibers designed to sustain high temperatures, such as those on avionics platforms. We tested different step-index 1-mm poly(methyl methacrylate) single-core and multicore fibers. Frequency response, bit error rate (BER), attenuation, and output power distribution were measured for each fiber type at room temperature. In addition, BER and fiber attenuation were monitored as a function of temperature, intentionally exceeding the temperature limits to obtain the true temperature ranges and to assess the performance penalty. The same properties were obtained for the overheated fibers and compared to those for nonheated fibers of the same type to reveal permanent performance degradation.**

***Index Terms*—Avionics optical systems, experimental characterization, plastic optical fibers, temperature-resistant fibers.**

I. Introduction

PLASTIC optical fibers (POF) have become a rapidly emerging media for transporting high-speed at low cost in the short-haul environment. Applications in automobiles and in-house systems and networks [1]–[3] have led this development and the airplane is the latest arena where they are becoming a serious alternative to glass fibers [4], [5]. More recently, POF has been suggested for the avionic platforms [6] by our industrial collaborator The Boeing Inc. Their increased diameter allows higher tolerance to vibrations and to dust particles that can totally obstruct light propagation in glass fibers; airplane cargo bays are generally dusty environments. Furthermore, glass fiber is harder to use and install even by trained personnel in the above platforms compared to POF and thus the use of POF in the commercial avionics environment can translate to significant cost benefits. POFs have moderate bandwidth-length products, but are flexible, resistant and can be coupled to cost-effective devices. In addition, although slow in their development [7], in the last years special large core poly(methyl methacrylate) (PMMA) fibers that can sustain temperatures up to more than 100 °C and thus, are capable of fulfilling the harsh environmental requirements for commercial aircraft data communication networks have become commercially available [8], [9]. These heat-resistant fibers are based in thermoset polymers that cross-link together during the curing process to form an irreversible chemical bond that eliminates the risk of melting when heat is applied [10]. The viability of a typical avionics telecommunication system with a large number of individual connectors and short POF segments was demonstrated using a time/frequency-domain approach that combined a matrix model for the fiber and optical connectors and the use of a commercial simulation tool [11]. However, the fiber model used in the simulation was experimentally obtained for a standard polyethylene jacket SC-POF that can only reach up to 80 °C, which is not enough for avionics environments where temperatures can reach as high as 125 °C. Also, multi-core plastic optical fibers (MC-POFs) have been proposed as a better option in avionics environments due to their improved insensitivity to bending but, whereas they share some of the advantages of ordinary SC-POFs, their bandwidths are narrower particularly at short lengths and highly dependent on launching conditions [12].

Therefore, our first aim in this paper is to assess the performance of POF-based communication links at room temperature comparing the performance of standard and heat-resistant fibers both single-core and multi-core by measuring different transmission properties under the same conditions and using the same equipment. Thus, we tested four different step-index 1-mm PMMA fibers: two single-core fibers and two 19-core fibers. Frequency responses, attenuation and radial profiles extracted from output far field patterns (FFPs) were measured for each fiber. The bit error rate (BER) as a function of data rate was also obtained using commercial transceivers designed for Gigabit Ethernet. Secondly, we measured the performance as a function of temperature for links based on the two single-core fibers. There are some works in the literature that explore the behavior of POFs under temperature variations within the manufacturer recommended range [9], [13]. Here, we intentionally exceeded the temperature limits to obtain the true temperature ranges and to assess the performance penalty. The frequency

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TABLE I
MAIN CHARACTERISTICS OF THE TESTED FIBERS

Fiber	GH-4001	BH-4001	SMCK-1000P	LHXE- 4001
Type	SC	SC	MC	MC
NA	0.50	0.58	0.60	0.58
Core diameter (µm)	980	980	1000	980
Attenuation @650 nm (dB/m)	0.17	0.20	0.18	n/a
Jacket diameter (mm)	2.2	2.2	2.2	1.5
Jacket material	Polyethilene (PE)	Crosslinked PE	Polyethilene (PE)	Crosslinked PE
Temperature range (ºC)	-55 – 85	-55 – 105	-55 – 85	-55 – 105

responses and radial profiles were obtained for the over-heated fibers and compared to those obtained for non-heated fibers of the same type. These measurements help us to assess if there is permanent performance degradation as a result of the over-heating.

The paper is organized into two main sections. In the first, the comparative characterization of the standard and high temperature fibers is presented, describing the measurement protocols and systems and showing the results. In the second section, the experiments and results of the temperature changes are presented. Then, all results are summarized and discussed, and finally, we present our conclusions.

II. Comparative Performance of Standard and High-Temperature POFs at Room Temperature

We have tested three different 1-mm PMMA fibers from Mitsubishi Rayon Co. Ltd.: two single-core fibers and one fiber with 19 cores. Two of these fibers have been specially designed to sustain high temperatures: BH-4001 (BH) and LHXE-4001 (LHXE), whereas the other is a standard GH 4001 fiber (GH). In addition, we tested another multi-core fiber the SMCK-1000P (SMCK) from Asahi that has a standard polyethylene jacket. All these fibers have step-index profiles. Table I shows the characteristics of the fibers as specified in their data sheets.

A. Experimental Set-Up and Characterization Protocol

The optical source for all the characterization experiments was the emitter side of a transceiver (EDL1000T-EVB from Firecomms™) that is based on a VCSEL at 665 nm. The emitter was connected to a 1-meter segment of the GH fiber via an OptoLock (OL) connector to maintain the same launching conditions throughout the experiments. All fibers tested were 20-meter segments and were connected to the 1-meter GH launching fiber through a VersaLink™ (VL) inter-connect. The output end of these fibers was finished differently depending on the equipment or measurements system to be used. The schematic of the complete experimental set-up is depicted in Fig. 1, including the equipment used for the measurement of frequency response, FFP and BER [12], [14], [15].

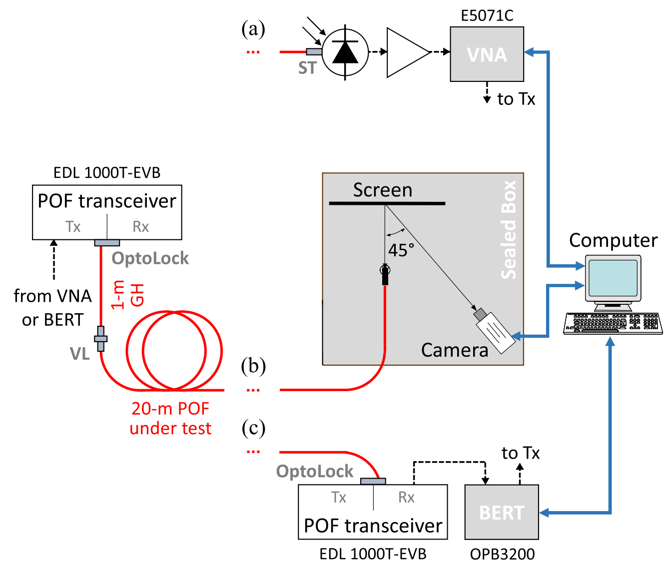


Fig. 1. Experimental set-ups for the characterization experiments. On the left, the launching system based on the Firecomms transceiver connected to a 1-m GH fiber is shown. On the right, the sub-systems to measure the (a) frequency response, (b) FFP, and (c) BER are displayed.

As the upper set-up of the figure shows, the frequency response of the fibers was measured using a Vector Network Analyzer (VNA E5071C from Agilent). We directly modulated the emitter in the EDL1000T EVB transceiver whereas the receiver was based on a 0.8 mm^2 Si photodetector (DET10A from Thorlabs), followed by an electrical amplifier (ZKL-1R5 from Mini Circuits). The fiber was connected to the detector via a ST connector as shown in the figure. The set-up in Fig. 1(b) shows how the fiber far field pattern (FFP) was obtained by recording the image reflected on a white screen placed opposite the fiber at 7.5 cm from its output end using a 12-bit monochrome cooled camera QICAM FAST 1394CCD. This sub-system was inside a sealed box to avoid spurious light as is shown in Fig. 1(b). The radial profile is extracted from this pattern and expressed as a function of the propagation angle to provide a good representation of the output angular power distribution. Finally, performance in terms of bit error rate was obtained using the BER Tester OptoBERT™ OPB3200 from Optellent. Inc. The set-up is shown in Fig. 1(c). The OptoBERT incorporates a pseudorandom binary sequence (PRBS) generator that supports continuously variable data rates from 100 to 3150 Mb/s. The PRBS pattern length was fixed at $2^{23}-1$. An OL connector was also used to connect the output end of the fiber to another Firecomms transceiver. Separate transceivers were used in order to avoid changes in the launching conditions during the measurements.

The experimental protocol was the following: First, the BER versus data rate, frequency response, and FFP were measured for the 1-meter GH fiber. The output optical power was also measured with a power-meter to be used as a reference for the subsequent measurements. Then, 20-meter fiber segments of each fiber type were prepared to connect to the 1-m GH reference with a VL connector that was kept fixed throughout

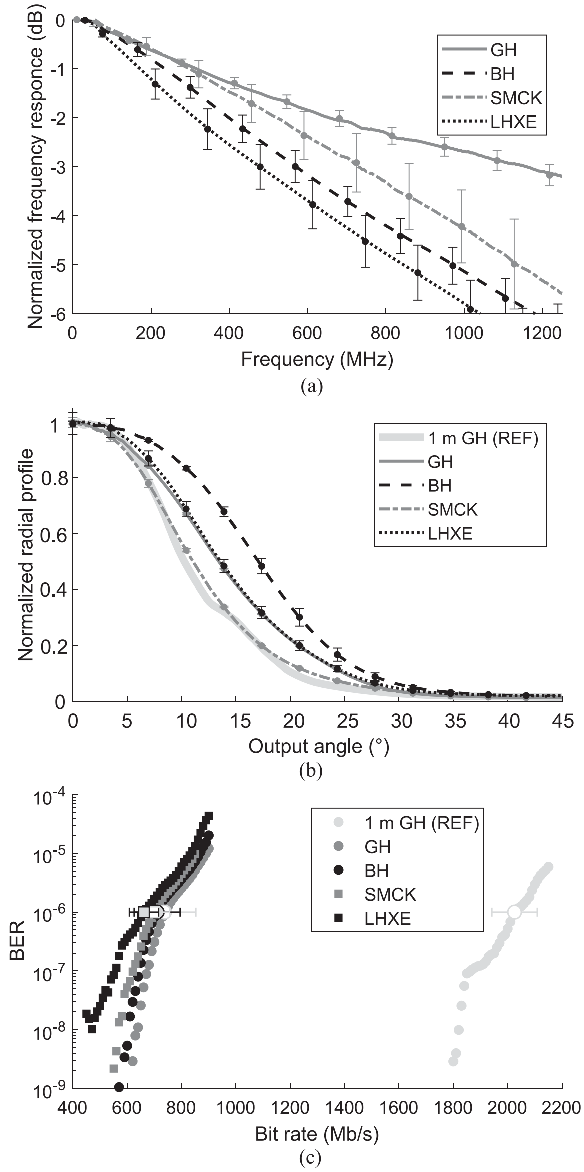


Fig. 2. Experimental characterization results for the SC and MC fibers considered. (a) Frequency response, (b) angular power distribution, and (c) BER versus bit rate.

its complete characterization. The other end was simply cleaved for insertion into the receiver part of the OL of the second transceiver to obtain BER versus data rate measurements. Next, the fiber output end was stripped to fit a VL to measure the tested fiber output power with the power-meter. This output end was then mounted and aligned in front of the screen of the FFP measuring set-up and several images of the FFP were recorded. Finally, we used the stripper to fit the end to the ST connector for the DET10A detector of the frequency response measuring system.

B. Results

The experimental data for all the fibers tested are shown in Fig. 2 and Table II.

TABLE II
OUTPUT OPTICAL POWER FOR THE TESTED FIBERS

Fiber	Average output power (dBm)	Standard deviation (dBm)
1-m GH (REF)	-3.20	0.22
GH-4001	-9.96	0.45
BH-4001	-10.50	0.28
SMCK-1000P	-11.70	0.75
LHXE-4001	-12.10	0.72

On the upper graph, the normalized frequency responses are plotted. To obtain the fiber frequency response without the effects of the system electronics, a reference obtained for the 1-m GH was used to normalize the results. The radial profiles extracted from the FFP images are shown in Fig. 2(b) including that of the 1-m GH. Finally, the BER versus data rate is shown in Fig. 2(c). The results show the average of at least 5 measurements obtained changing the termination of the output end of the fiber. Error bars have been included in each curve to give an estimate of their variability. In the BER plots, the horizontal bars show the standard deviation of the data rate with an error rate of 10^{-6}. Table II shows the output power at the end of the fibers that is the result of the average of several measurements along with their standard deviations.

These results show that the performance of the GH fiber in terms of frequency response is well above that of the standard multi-core fiber and the heat-resistant fibers. Also, the single-core fibers have better performance than the multi-core fibers with the same jacket. There are also significant differences in the angular power distributions between fibers: the multi-core fibers display narrower profiles than the single-core ones with the same jacket, whereas the heat-resistant fibers have wider profiles than the corresponding standard models. BER plots, however, show high variability but only slight differences between fiber types, which are less impressive than could be expected from the remarkable differences in the other metrics. Nevertheless, the BER curve measured for the 1-meter reference GH demonstrates that the limitations imposed by the 20-meter fibers are significant compared to those imposed by the transceiver itself.

III. Performance of Single-Core Standard and Heat-Resistant POFs Under Temperature Changes

In a previous work, we verified that the performance of these fibers when the temperature was changed inside the operating ranges recommended by the manufacturer was unaltered [15]. Here, we tested the variation with temperature of transmitted power and BER for both SC-POFs intentionally exceeding their high temperature limits. The 20-meter segments of the GH and BH fibers used for the over-heating experiment came from the same reels than those characterized in the previous section.

A. Experimental Set-Up and Characterization Protocol

The schematic in Fig. 3 shows that the input end of the fiber was connected directly to the emitter side of the transceiver whereas the output end was connected through a VL interconnect to the trunk of a Y-splitter, which was custom made

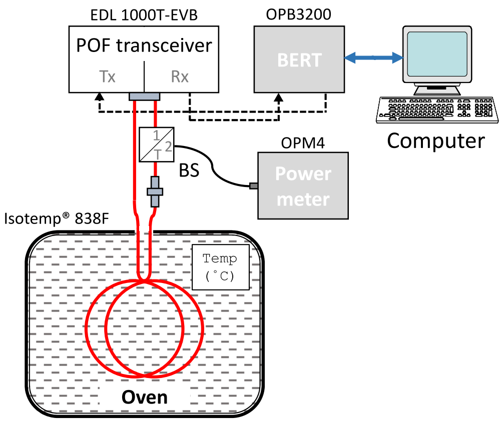


Fig. 3. Experimental set-up for the temperature experiment. The schematic shows the POF link designed to measure output power and BER simultaneously using a BS while changing the temperature with the oven.

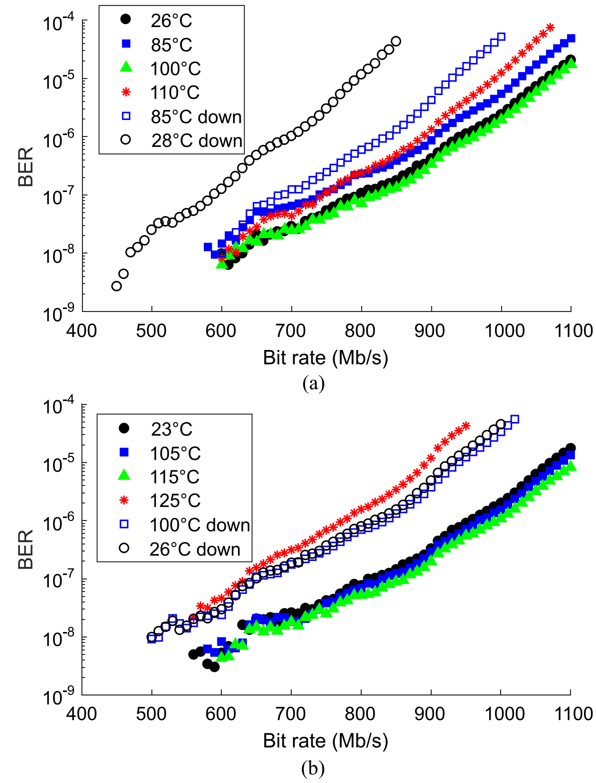


Fig. 4. BER versus bit rate for (a) the GH standard SC-POF and (b) the BH heat-resistant SC-POF as obtained at different temperatures.

for POF by OZ Optics Ltd. One of the ports of the splitter was connected to the receiver and the other to a power-meter to monitor power changes during the measurements. Both transceiver connections were achieved through OL connectors. To control the changes in temperature we used a Fisher Scientific Isotemp 838F oven. It is a forced air, programmable oven with PID microprocessor control at operating temperatures up to 325 °C [16]. The oven is equipped with two LED displays to show the target and current temperature settings, respectively. The 20-meter fiber segment was rolled with a 20-cm diameter and introduced into the oven. The two fiber ends exited the oven through an upper hole leaving outside two 50-cm segments to connect to the equipment as described before. Since we are only interested in the performance of the fiber as the temperature changes, the rest of the equipment was placed outside of the oven and operated at room temperature. Humidity was not controlled or measured during the experiments. The relative humidity inside the oven ranged from 50% for room temperature to less than 20% for the highest temperatures considered.

The measurement protocol was the following: first, with the fiber placed into the oven and the system set-up completed, the received power and BER versus data rate were measured under normal room conditions (i.e., before heating the fiber), to serve as a reference. Once these measurements were taken, neither the fiber nor the rest of the equipment was changed throughout the experiments to avoid introducing additional variability. Then, the oven was set to increase its temperature slowly (at a rate of 1 °C per minute) up to the limit set for the experiment. BER versus data rate and power were measured only at some discrete temperatures. Once the maximum temperature was reached, it was decreased at the rate of less than 1 °C per minute down to room temperature, and power and BER were also monitored.

B. Results

Fig. 4 shows the BER results for the GH standard fiber (a) and the BH heat-resistant fiber (b). The solid circles represent the BER when raising the temperature and hollow circles correspond to measurements when the temperature was decreased, after heating the fibers above their specific limits (i.e., up to 105 for the GH and 125 °C for the BH). The received power versus temperature will be shown later in the discussion.

As can be observed, even operating under the recommended temperature range, measurements show a higher variability of the transmission performance for the GH fiber. Moreover, the cooling down process further increased its error rates. As for the BH fiber, BER measurements show that this fiber has almost no transmission penalties even exceeding its nominal limit up to 125 °C, when its performance suddenly drops. During the cooling down process, the BER values slightly decreased, but they do not recover their initial values. Note, that for both fibers, the BER curves shown in Fig. 4 have a different shape than those obtained in the characterization experiments. We attribute this fact to the different launching conditions and to the presence of the Y-splitter at the fiber receiver end [17]. Moreover, this effect led to higher attainable data rates.

Later on, output power distribution and frequency responses for the two over-heated fibers were measured, following the procedure described in the first section. Fig. 5 shows the results and compares them to those in the previous section obtained for non-heated fibers from the same reel (gray and black lines for the GH and BH fibers, respectively). Both measurements show significant changes in the performance of the GH fiber with the standard jacket when its temperature limit is exceeded and negligible changes for the heat-resistant BH, what reveals the resistance of the latter to temperatures as high as nearly 125 °C.

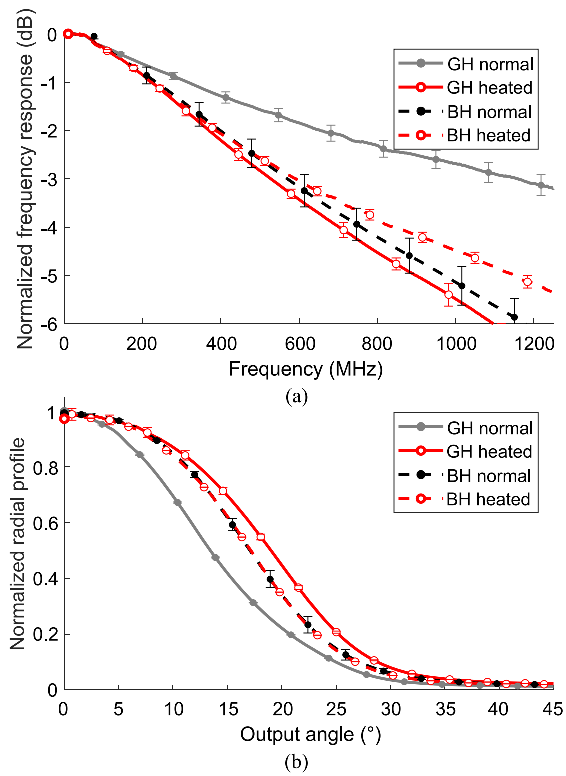


Fig. 5. (a) Frequency responses and (b) optical power distributions for the over-heated single-core fibers in comparison with un-heated fibers.

TABLE III
CHARACTERISTIC PARAMETERS OF THE TESTED FIBERS

Fiber	Power Loss (dB)	3-dB Bandwidth (MHz)	Output HWHM (°)	Bit Rate @10^{-6} (Mb/s)
REF	–	–	10.3	2025
GH-4001	-6.8	1143	13.5	738
BH-4001	-7.3	564	17.1	710
SMCK-1000P	-8.5	717	11.1	699
LHXE-4001	-8.9	478	13.6	662

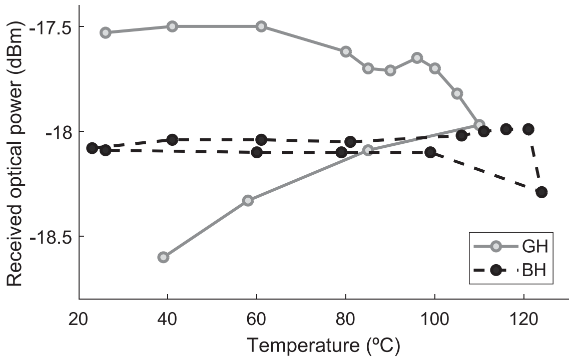
IV. DISCUSSION

The results of the characterization experiment show substantial differences between different fiber types, depending both on the number of cores and of the jacket material. To compare the performance of the fibers and quantify their behavior, Table III shows some parameters extracted from the measurements in Fig. 2. The −3dB optical bandwidth is obtained from the frequency responses; the half-width at half maximum (HWHM) from the normalized angular power distributions and, the bit-rate for a BER of 10^{-6} from the BER versus bit-rate curves. The power loss is obtained from the mean values of measured output power shown in Table II. This power loss is not the attenuation for the fiber but also includes the VL inter-connect loss.

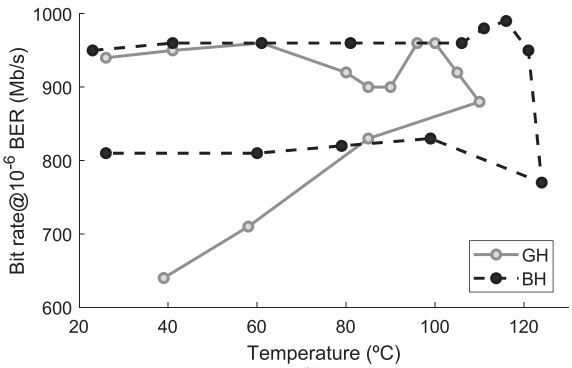
The higher power loss of the heat-resistant fibers of each type relative to the standard ones can be attributed to the higher attenuation of the thermoset plastic relative to the thermoplastics [10]. The measurements also show that power loss is significantly higher for the multi-core fibers than for their single-core counterparts. This difference cannot be totally attributed to the attenuation introduced by the different fibers. In fact, the connector loss is higher for the multi-core fibers as has been demonstrated [18]. The bandwidth for the GH fiber, single-core with a standard jacket, is nearly twice the bandwidth of the BH fiber, and significantly greater than the bandwidth for both multi-core fibers. The LHXE fiber, with 19 cores and a heat-resistant jacket has the lowest bandwidth. Also, the output power distributions are wider for the heat-resistant fibers than for the corresponding standard fibers of the same type. For the single-core fibers, this fact is consistent with a higher diffusion in the heat-resistant fiber. Higher diffusion induces power transfer among modes which means greater modal dispersion that is correlated with its lower frequency response. Also, the heat-resistant multi-core fiber displays a wider output power distribution than the standard multi-core, and so the former has a narrower bandwidth than the latter. On the other hand, our measurements show that the output power distributions for the multi-core fibers are narrower than those for the corresponding single-core fibers with the same jackets, although their bandwidths are lower. We argue that the dispersion for MC-POFs follows different mechanisms than for SC-POFs and is determined both by intra-core diffusion and by differences between cores [12].

The BER measurements presented show that the transceiver does not pose a limit to performance as the bit rate for the acceptable BER of 10^{-6} is 2 Gb/s under back-to-back conditions. However, although the frequency responses for heat-resistant fibers are poorer than for the standard fibers (see Fig. 2), the differences between the measured BER and bit-rate limits at 10^{-6} are insignificant. We suggest that this is due to the processing over the received signal performed at the transceiver, which can compensate for some power loss or signal distortion. When the fibers undergo over-heating, however, the performance of the heat-resistant fiber is better. The variation of received power and bit rate at a BER of 10^{-6} as a function of the temperature extracted from the curves in Fig. 4, is shown in Fig. 6(a) and (b), respectively.

As the measurements show, the performance of the GH fiber degrades when heating from 60 °C to 80 °C. The received power has a decrease of 0.12 dB and the bit error rate at 10^{-6} BER suffers a downward shift of 40 Mb/s. When the recommended operation temperature is exceeded transmission behavior changes even recovering at 95 °C, whereas received power does not reach its initial value. Both data rate and received power decrease again from 100 °C to 110 °C, and then, even more steeply and constantly during the cooling down process. This effect might be related to the shrinkage experimented by the standard thermoplastic fiber while cooling down after being melted. Final values are 300 Mb/s and 1 dB below the initial ones, respectively. The degradation is confirmed by the comparison of the frequency responses in the over-heated and non-heated GH in Fig. 5(a). Bandwidth for the over-heated GH is now 527 MHz, revealing an important reduction compared to the initial 1143 MHz for the non-heated fiber. The power distribution has a width of 19° for the over-heated GH, much wider than for the non-heated GH (13.5°) exhibiting an important increase in diffusion which correlates to the degradation in its frequency response [19], [20].



(a)



(b)

Fig. 6. (a) Receiver power and (b) bit rate at 10^{-6} BER as a function of temperature.

On the other hand, the BH fiber showed a behavior more stable than the GH when operated within the recommended temperature range. Even when the specified limit is exceeded, we found only small power changes with temperature. However, when temperature was increased from 115 °C to 125 °C, sudden performance degradation was observed: a 220 Mb/s data-rate downward shift and a decrease of 0.3 dB in received optical power. However, in contrast to the GH fiber, the cooling down process allowed some recovery and further stabilization of both measured parameters, as expected from the thermoset material of this fiber. This recovery was confirmed later on by comparing its frequency response, and output power distribution with those of a non-heated BH fiber, which are very similar. The bandwidth: 586 MHz and angular output width: 17.2° have values close to those obtained for the un-heated BH shown in Table III.

V. Conclusion

As POFs are penetrating the telecommunications area and in particular the avionics field, their performance in terms of changing temperature conditions becomes vital. We found that single-core fibers show better transmission characteristics than multi-core fibers although these fibers have the advantages of lower curvature losses and the possibility of increasing its capacity by spatial multiplexing. The heat-resistant fibers have poorer basic properties (attenuation and bandwidth) than their standard counterparts although the resulting BERs are similar due to the compensating mechanisms of the transceiver. The high temperature single-core performed very well within the specified operating temperature ranges. That is, both the BER and measured transmitted power remained insensitive to the temperature changes and, even when the limits specified by the manufacturer were exceeded, the changes in its basic parameters were small, whereas the performance of the standard GH fiber showed some variability with temperature within the specified operating range and a permanent degradation when exceeding this range.

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