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Thermal Influence on Plastic Optical Fibers: A Reliability Study

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In the last years, the phenomenon called Fourth Industrial Revolution has promoted an intense digitalization of data and the automation of several processes in real-time, bringing concepts such as the internet of things, smart cities and cloud computing. From this scenario, optical fibers have become key elements as optical sensors or, mainly, composing optical networks due to the possibility of transmitting data in high frequency over long distances without big losses. In the specific case of optical fiber sensors, other important points also have contributed to their popularization. In the face of this increase in interest in optical fiber devices, this work presents a reliability analysis from a brief study of how thermal effects may affect the operation of devices based on POFs and also aims to identify failure modes after performing accelerated life tests. This study was subdivided into two different steps: firstly, the behavior of the optical power level was measured during all heating processes and, after this first step, also performed analyses using microscopy to locate possible mechanical changes in POFs structures.

Keywords: plastic optical fiber, accelerated life testing, fault diagnosis, prognostic health management, reliability engineering.

1. Introduction

In the last decades, society has experienced a comprehensive modernization process promoting a high degree of digitalization in several fields. This process changes the connectivity concept to another level and contributes actively to establishing optical fiber as one of the most important technologies currently Winzer (2015). This increasing importance also contributed to expanding the presence of optical fibers beyond high- performance communication networks, resulting in their presence in applications such as sensing and biomedical devices Yadav et al. (2018). The rapid diffusion of this technology has a direct relation with the characteristic properties of the optical fiber that impose important advantages in relation to traditional electrical and mechanical systems Winzer (2015). Optical fibers have a high bandwidth and a low attenuation coefficient, allowing the transmission of a large amount of data at high speed and over very long distances Agrawal (2021). Physical properties such as flexibility, small size and lightweight also contribute to this process, figuring optical fiber systems as interesting solutions to several applications Haus (2010). Moreover, the signal transmission in these devices has a high-reliability degree because optical fibers are resistant to conditions that be challenging to the operation of other types of systems Haus (2010). For example, optical fibers in usual conditions are immune to electromagnetic interference, do not generate sparks or heat and promote complete isolation between the signal Haus (2010). These features allow the operation of optical fiber devices in harsh conditions, such as in corrosive media, explosive atmospheres or submerged Haus (2010); de Barros et al. (2022).

To further expand the possibilities of applications, different technologies of optical fibers are continuously developed, changing structures, dimensions or the material used in their construction. Among these, two popular types of optical fiber are Single-Mode Fiber (SMF) and Plastic Optical Fiber (POF) Agrawal (2021). The first is the most traditional technology, being composed mostly of silicon dioxide (SiO_2) and with a diameter that usually does not exceed 125 micrometers to cladding and 8 micrometers to the core, is an optical fiber widely studied in several aspects and applications, being often used as a reference in studies about other technologies Haus (2010).

The POFs, on the other hand, is an emerging technology that has been a growing subject of research due to some properties such as its higher refractive index value and greater mechanical resistance Agrawal (2021). This last feature is directly related to the traditional POFs dimensions: a diameter of 1 millimeter, eight times bigger than the SMF diameter. The main material used in POF construction is polymethyl methacrylate (PMMA) Leal-Junior et al. (2018), a synthetic polymer with thermoplastic properties Leal-Junior et al. (2018). Fig. 1 illustrates these two technologies of optical fiber.

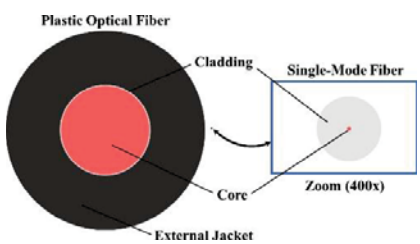


Fig. 1. Representation of a plastic optical fiber (POF) and a single-mode optical fiber (SMF).

Despite the advantages already mentioned in relation to SMFs, the use of the PMMA in POFs construction reveals an important limitation in the adoption of this technology: the operating temperature range. While SMFs can operate without major problems in temperatures above 400°C e Silva et al. (2020), manufacturers do not costume present information about POFs operating in temperatures above 85°C. From all this context, this work proposes a brief evaluation of POF performance operating in thermal stress conditions, analyzing changes in the physical structures of optical fiber and its optical parameters, allowing a better understanding of how elevated temperatures can affect systems based on POFs. Another important point is that after a systematic review of the literature, no studies were found that focused specifically on fault diagnosis involving plastic optical fibers, so this work also intends to be a starting point for more detailed analyzes in further studies.

2. Materials and Methods

The first step to evaluate the POFs thermal response was the development of an optical power meter (OPM) capable of performing continuous measures in real-time. This device is especially useful because, through this type of measurement, it is possible to evaluate the behavior of the optical signal during thermal stress, contributing to the identification of failure modes. Fig. 2 illustrates this optical power meter through a block diagram representation.

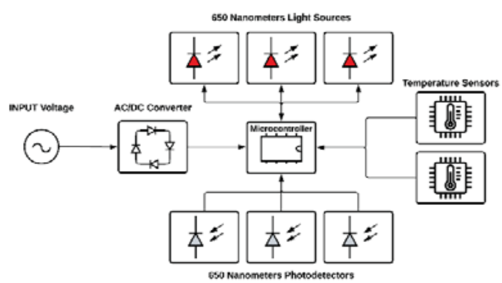


Fig. 2. Representation in blocks diagram of the optical power meter developed.

Basically, the OPM structure can be subdivided into the power circuit, represented in Fig. 2 by the AC/DC converter block, the light source circuit and the control and acquisition system. The first is responsible to supply energy to all other components, through the conversion of an AC input voltage ($220V_{AC}$/60Hz) into the DC voltage required by the other components

($5V_{DC}$). With this purpose, this circuit was composed of rectifiers diodes, capacitive filters and a voltage regulator. As light sources were used light-emitting diodes (LEDs) which emit an optical signal with a wavelength of 650 nanometers, the region of least attenuation according to the manufacturer and the wavelength typically found in literature about POFs applications de Barros et al. (2021, 2022).

These LEDs also were characterized aiming to determine the relationship between the optical power emitted and the current of operation. This step is fundamental because allows compensation of any variations in the measurement process due to voltage fluctuations, improving the accuracy in the evaluation of attenuation behavior during thermal stress. The characterization was performed from the data provided by the manufacturer Broadcom (2016). Fig. 3 shows the curves which synthesize this data.

The last component of the OPM is the control and acquisition system. This circuit is composed of different sensors, a processing unit and a human-interface support system that, together, have the functions of evaluating in real-time the optical power levels transmitted and received, measuring the operating temperature and displaying all this data to the user. To manage the transmission levels, the current of each LED used is measured and this information was used as a corrective parameter and to measure the reception levels, PIN 650 nanometers photodiodes were used as detectors.

The heating process was performed using a digital microprocessed muffle furnace (SPLabor - SP- 1200 DM/G). To measure the temperature during the heating process, two DSB18B20, 9-bit digital thermometers were used together with the internal thermometer of the muffle furnace. The use of this last thermometer was especially useful in higher temperatures due to the DSB18B20 limitations in temperature operation over 125°C Dallas (2019). To avoid any thermal effect on the light sources, the LEDs were insulated from the furnace and operated refrigerated under the action of an air cooler.

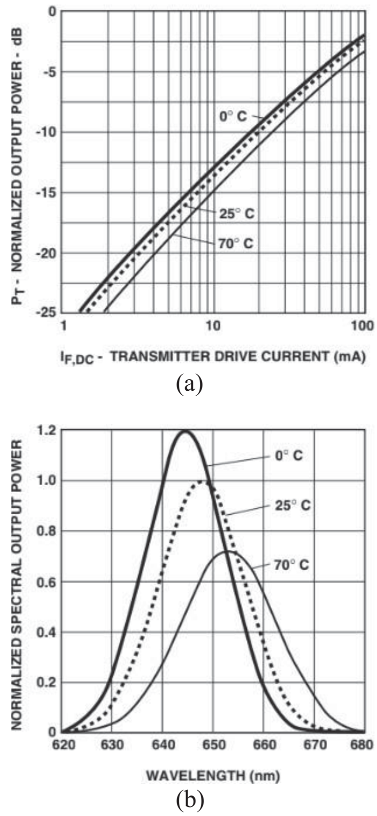


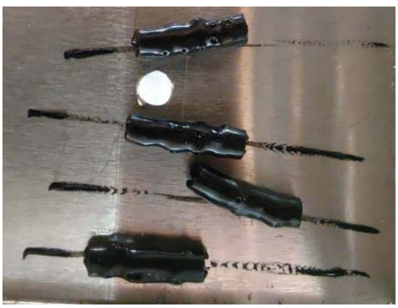
Fig. 3. Characteristic curves provided by the manufacturer. (a) - Relationship between normalized output power and operating current. (b) - LED emission spectrum. Source: Broadcom (2016).

Two different methodologies were used. Firstly, optical fiber segments were heated for one hour and analysis using microscopy was performed to evaluate the impact of heat on the physical structure. The second methodology applied was the behavior analysis of POFs cables with one meter of length during their operation. In this second case, the heating occurred in stages, aiming to determine the failure point and the effects with each temperature increase. Also it was possible to determine a point which the POFs attenuation increases continuously even if the temperature decreases: the critical point. In both methodologies, POFs were used with and without an external polyethylene coating, aiming to evaluate the contribution of this protective layer.

3. Results and Discussions

The most visible consequence of the thermal stress on POFs was the changes in their physical structure. As shown in Fig. 4, the POFs have a significant contraction process in high temperatures. This phenomenon can be observed from temperatures over 90° C and promotes the occurrence of bends, contributing to increasing optical power losses.

(a)



(b)

Fig. 4. POFs after the heating process. The blue line in (a) marks the original size of the POF. In (b) also is possible to see the original size through the black lines from polyethylene melting.

Due to the contraction process, different bend patterns can be observed according to the original position in which the fiber was heated. Fig. 5 shows the medium value measured for different temperatures. These bend patterns were repeated for optical fibers with and without the external coating and some of these patterns are shown in Fig. 6. This last observation can be indicative that, despite the increase in mechanical resistance, an external coating does not offer any kind of additional protection against thermal effects. Moreover, from the results shown in Fig. 5, plastic optical fibers with coatings presented a higher degree of contraction, increasing the tension and, consequently, facilitating breaks and the degradation of the optical fiber core.

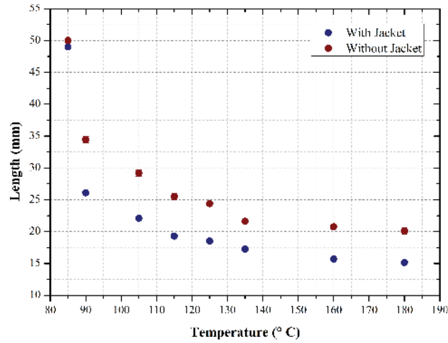


Fig. 5. Medium lengths of POFs segments after the heating process in different temperatures.

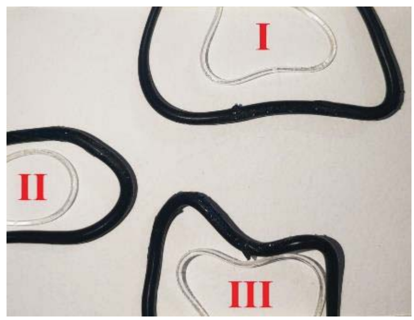


Fig. 6. Some bend patterns obtained after the heating process. Each of these patterns is associated with a different insertion position before the heating process.

A consequence of the contraction process is an increase in diameter in the heated region and a simultaneous decrease in diameter in other regions. This behavior also can be observed in optical fiber with coating where this outermost layer appears to have gone through the same process, reinforcing the argument mentioned earlier. Another effect directly related to the contraction process is an increase in optical fiber traction, possibly causing breakage in some cases.

The second type of failure mode evaluated was the one related to the failures during POFs operation through the variation of its optical parameters due to the thermal stress. This dynamic can be visualized in Fig. 7, where it shows the variation of the optical power level guided by the optical fiber.

The curves shown in Fig. 7 were obtained from the average of sample responses and show a similar behavior between POFs with and without coatings. As also shown in Fig. 7, the optical power level transmitted varies significantly for temperatures higher than 85°C, being in accordance with the recommendations of the POFs manufacturer. After the sudden drop in the transmitted power at 85°C, as the temperature increases, the optical power level remained approximately constant up to 115°C: the critical point. From this temperature, the optical fibers were rapidly degraded and the transmitted power is reduced even with a decrease in temperature. This second drop may be a consequence of the strong retractions suffered by the optical fibers at this temperature, which promote pronounced curvatures.

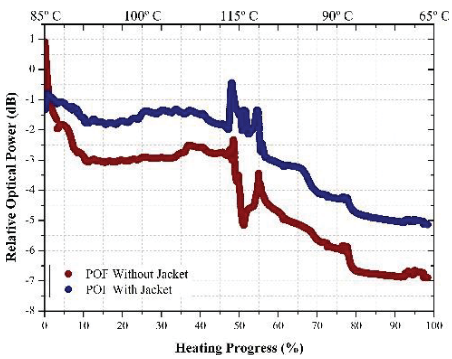


Fig. 7. Average variation of optical power levels transmitted in the optical fiber during heating.

At higher temperatures (above 135°C), it was observed melting in both types of optical fibers. For this situation, multi-channel optical cables, composed of more than one POF, are quickly rendered useless due to the fusion of these channels (see Fig. 4a). Moreover, during peaks in heating, even if the POFs do not instantly melt, the optical signal level drops drastically due to the appearance of bubbles inside the optical fiber, as shown in Fig. 8.

In Fig. 8 is also possible to identify a complete geometry mischaracterization resulting in a bulging which compromises the POF functioning. A similar result can be observed in optical fibers with coating as shown in Fig. 9.

(a)

(b)

Fig. 8. Plastic optical fiber without the coating before and after heating at 140°C.

Fig. 9. Effect of heating at 140°C in optical fiber polyethylene coating.

4. Conclusions

This work presents a preliminary study of the thermal effect on two different technologies of plastic optical fibers operation: standard plastic optical fibers and plastic optical fibers with polyethylene coatings. This work also aims to support further works that will allow to study in more detail the failure occurrence to determine the reliability of systems based on plastic optical fibers. Changes in physical parameters such as length and thickness as well as changes in optical attenuation were evaluated through the use of a microprocessed muffle furnace, an optical power meter developed specifically for these experiments and optical microscopy. Different failure modes can be identified due to the occurrence of contractions, resulting in breakage by traction, the emergence of bends and bubbles, increasing optical power losses, and melting at higher temperatures.

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