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# Damage in Optical Fiber-based Sensors in Extreme Environments For High Flux Solar Measurements

**Manuel Jerez[1*], Alejandro Carballar[1], Ricardo Conceição[2], José González-Aguilar[2]**
*[1]Electronic Engineering Department, Universidad de Sevilla (E.T.S. de Ingeniería), C/ Camino de los Descubrimientos s/n, 41092, Sevilla, Spain*
*[2]High Temperature Processes Unit, IMDEA Energy, Av. Ramón de La Sagra, 3, 28935 Móstoles, Madrid, Spain*
*Correspondence: mjerez@us.es*

**Abstract:** Physical damage in optical fibers when acting as irradiance probes in a high-flux solar simulator is analyzed through SEM. Coating degradation and relative displacement of the fiber due to local intense heat fluxes are observed. © 2025 The Author(s)

## 1. Introduction

Optical fiber sensors have transformed measurement systems through their superior features that allow them to be a competitive alternative to state-of-the-art technologies for extreme environments [1]. Their potential application in central receiver concentrating solar power (CSP) to monitor irradiance and temperature are particularly attractive in working conditions that comprise solar radiation fluxes above 1 $MW/m^2$ and temperatures over 1000 °C. The use as incident solar radiation fluxes collector was already demonstrated at low irradiances when acting as radiometers [2]. Besides, optical fiber sensors allow the spatial decoupling of sensing and measurement components, while operating under harsh environmental conditions [3-5]. However, exposure to extreme temperatures and high-flux radiation may lead to structural modifications and signal degradation, which potentially affect measurement accuracy and long-term reliability [5]. In this work, the analysis of the damage in optical fibers when operating as radiation collectors in a high-flux solar simulator is presented, following the inspection of the fibers using a Scanning Electron Microscope (SEM).

## 2. Methodology

The optical fibers tested and analyzed in this work were specifically customized for measuring high concentrated solar radiation fluxes as those expected in solar receivers in point-focusing technologies (like solar towers and parabolic dishes) by Engionic, Berlin, Germany, to withstand up to 700 ºC. The core of the optical fibers is surrounded by a special coating made of either gold or polyamide within a steel capillary filled with alumina, as shown in Fig. 1a. Experiments were performed in the high-flux solar simulator (HFSS) KIRAN-42 at IMDEA Energy, Móstoles, Spain, a facility able to emulate the high-radiation fluxes observed in concentrating solar technologies. The HFSS is capable of achieving a peak flux up to 3.6 $MW/m^2$ at the focal point. Tests were conducted achieving 400 $kW/m^2$ and 500 ºC using 2 of the 7 lamps composing the facility.


(a) (b) (c)

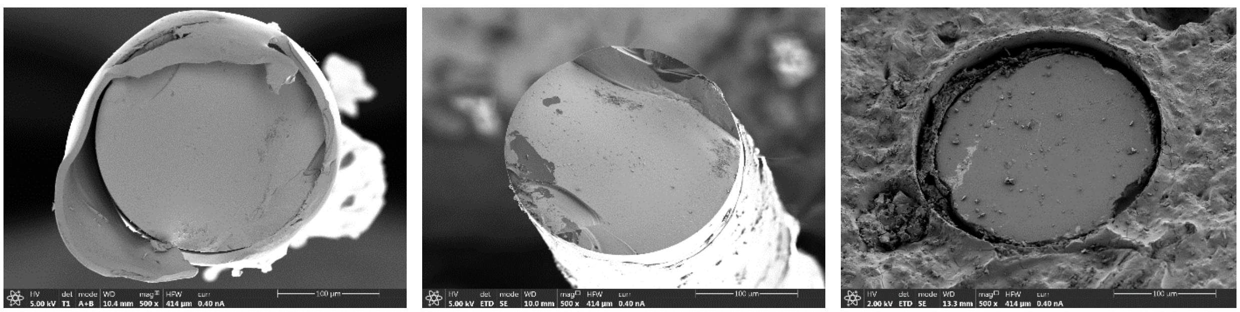
Fig. 1. SEM micrographs of the optical fiber tips: (a) optical fiber with gold coating before exposition to radiation; (c) gold-coated optical fiber after experiment in the high-flux solar simulator, and (c) polyamide-coated optical fiber after testing.

After the experiments conducted in the high-flux solar simulator, the tips of the optical fibers were examined using a SEM (Thermofisher Teneo) located at the Research, Technology and Innovation Centre of the University of Seville (CITIUS), Spain. Comparative analyses were performed between the exposed fibers and unused fibers of the same specifications to assess the effects of the extreme conditions applied.

## 3. Results

Fig. 1a and b show the tip of the optical fibers with gold coating before and after exposure in the high-flux solar simulator, respectively. Fig. 1c presents the tip polyamide-coated optical fiber after testing. Before the assays, the cohesion in the different parts composing the design can be visualized, as well as the correct placement of all the elements on the same plane. However, the core and cladding of optical fibers presents a significative retraction with respect to the original position at the surface of the capillary, which might be due to thermal expansion and contraction processes of the different materials. This phenomenon may lead to possible shadowing effects when measuring the concentrated solar flux. Besides, the post-exposure analysis by SEM of both gold and polyamide coatings reveals distinct degradation patterns. The gold-coated optical fiber presents an additional deformation of the gold coating that appears slightly expelled from the alumina substrate, as illustrated in Fig. 1b. The polyamide-coated optical fiber shows the complete elimination of the polyamide resulting in a void formation between the fiber core and the capillary filling material, as shown in Fig. 2c.

To solely assess the effect of temperature on the fibers and isolate it from any influence induced by radiation, a polyamide-coated fiber without the metallic capillary was used. The objective was to analyze the volatilization of the coating previously observed. In this case, the fiber was examined under a microscope prior to exposure to any extreme conditions, exhibiting the appearance shown in Fig. 2a. Subsequently, the fiber was subjected to 600 °C for 15 min and re-examined under the microscope, yielding the result shown in Fig. 2b. It is observed that the heating process completely removed the coating material, suggesting that prolonged high thermal exposure, even within the specifications provided by the manufacturer, may also impact the fiber structure. Along with this fiber probe, a completely manufactured fiber with alumina coating that was never exposed to radiation, was placed on the furnace. The results from this experiment are illustrated in Fig. 2c, where the fiber not only shows signs of degradation in the coating material, but also a small retraction from the tip of the fiber inwards.



(a) (b) (c)

Fig. 2. Scanning electron micrographs of a polyamide-coated optical fiber without steel capillary: (a) before; and (b) after thermal treatment at 600 ºC for 15 min in a tubular furnace; and (c) optical fiber assembly with polyamide coating after the same thermal treatment.

## 4. Conclusions

The present research demonstrates that all fibers exposed to high flux densities and temperatures undergo significant structural modifications. The main finding was the shift in position observed in all specimens, where the retraction of the fiber and the protrusion of the gold coating might cause power loss through the shadowing of the core. The alumina-filled metallic capillary showed changes across all specimens, although this should not impact measurements, since the alumina only acts as thermal insulation. Testing revealed that polyamide is unsuitable for coating optical fibers in this particular application, showing worse behavior than gold fibers and degradation at high temperatures, even during short exposure time. Gold coating proved to be the best choice, maintaining its stability even in extreme conditions.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