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Optical Fiber as Solar Radiation Collector for Radiometric Measurements

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Abstract. The feasibility of using optical fibers as solar radiation collectors in radiometric measurement devices and instruments is discussed, taking into account the various characteristics of the fibers that affect the measurements, with a special focus on numerical aperture. The discussion is supported by various results using the fiber to measure direct normal irradiance.

Keywords: Solar Irradiance, Direct Normal Irradiance, Pyrheliometer, Optical Fiber

1. Introduction

Solar energy is a resource that plays a crucial role in the energy consumption nowadays, leading the transition towards sustainable energy systems. Data collection on solar irradiation is important for a wide variety of applications, such as agriculture, architecture or medicine; but also for the energy generation field; allowing investors and companies to evaluate the potential of different spaces for the installation of photovoltaic or concentrated solar power (CSP) stations, and helping the real time monitoring of efficiency, status or potential problems in this type of power generation plants.

Solar irradiance is defined as the radiant flux received by a surface per unit area. The intensity of the received radiation and, in consequence, the solar irradiance measurement varies across Earth’s surface, influenced by geographical location, season of the year, time of day and meteorological conditions. Solar irradiance is decomposed into two main components, depending on the source of the sunlight. On one hand, we refer to direct normal irradiance (DNI) when talking about the solar radiation coming directly from a small solid angle centered in the solar disk, i.e., the direct beam. On the other hand, the diffuse horizontal irradiance (DHI) refers to the radiation received from any path but the one directly from the sun, and which is received from the atmosphere due to the scattering, reflection, and other interactions between light and the suspended particles surrounding the earth. The sum of both components is known as global horizontal irradiance (GHI) [1].

Following International Organization for Standardization (ISO) [2] and World Meteorological Organization (WMO) [3] norms, the device used for measuring DNI is the pyrheliometer. This device is mounted on a solar tracker, making sure that the system is always oriented towards the sun, capturing the radiation coming from the solar disk. The captured radiation will be guided to a thermopile, converting the induced heat into a voltage signal [4]. Apart from being mounted on a sun tracker system, the pyrheliometer needs to guarantee that only the radiation coming from the solar disk is captured. For this reason, the field of view of the device must be sufficiently small. According to the World Meteorological Organization, a pyrheliometer should have a half-angle aperture of 2.5º, although other studies have explored half-angle apertures up to 10º [5].

In this work, optical fiber is proposed as the instrument for capturing solar radiation in radiometric measurements. The key parameters influencing the measurement are the core diameter, which determines the power coupled into the fiber, and the numerical aperture (NA), which defines the fiber's field of view, dictating whether the proposed device can behave as a pyrheliometer. This study discusses results obtained from several types of optical fibers.

2. System description

The proposed system is depicted in Figure 1: the tip of the optical fibers is exposed to the solar light, guiding the captured solar radiation to a photodetector which transforms the optical power into an electrical signal received at an optical power meter, generating a power trace used to estimate the solar irradiance. The benefits of this configuration are multiple. First, by separating the solar radiation collector from the optical power measurement device, more stable and temperature-controlled measurements are achieved, as heat and radiation do not directly impact the detector. Additionally, the ability to modify the optical fiber used allows for adjusting the captured optical power magnitude and the acceptance cone of the incident solar radiation, ensuring that only radiation from the solar disk is received. Lastly, its geometry makes it suitable to be installed directly in a PV panel or heliostat, providing solar irradiance directly measured on one of these devices. Beyond the technical benefits, the device's cost is significantly lower than that of a commercial pyrheliometer.

In order to perform the different tests, the exposed tips of the optical fibers were mounted on the KIPP & ZONEN SOLYS Gear Drive solar tracker to ensure continuous sun tracking throughout the day. The other tip of each fiber was connected to a THORLABS S140C silicon photodiode and a THORLABS PM320E optical power meter. Alongside the different fibers on the solar tracker, a commercial KIPP & ZONEN CHP1 with a half-aperture angle of 2.5º pyrheliometer was placed, generating a solar irradiance measurement used as a reference to evaluate the behavior of the different fibers. Figure 1(a) shows the fiber tip located next to the commercial pyrheliometer, while Figure 1(b) shows the fiber tip connected to the photodiode, as well as the optical power meter.

(a) (b)

Figure 1. *Experimental setup for the tests. (a) Optical fiber placed next to a commercial pyrheliometer on a solar tracker, and (b) silicon photodiode and optical power meter.*

After processing the optical power trace with a calibration algorithm already presented in [6], the optical fiber and photodiode-based radiometer, depicted in Figure 1, provided accurate direct solar radiation measurements. The necessity of the calibration algorithm is due to two main factors. The first is that semiconductor photodiodes do not have a plain response curve covering all the solar irradiance spectrum; the second is the losses introduced by the optical fiber between the exposed to radiation tip and the photodiode, which are also irregular depending on the different wavelengths of the radiation transmitted. The latter, nevertheless, is negligible in our application, as fiber attenuation coefficients are small enough for 20m length of fibers used.

3. Results

All the fibers evaluated as capturing elements were manufactured by THORLABS, varying its core diameters from 50µm up to 200µm, while numerical apertures assessed were 0.1, 0.22 and 0.5, resulting in half-angles apertures of 5.7º, 12.5º and 30º, respectively. The optical fiber models used, and its technical specifications are summarized in Table 1.

Table 1. *Details of the optical fibers used as capturing element for the irradiance measurement.*

Fiber Model	**Core Diameter (µm)**	**Numerical Aperture**	**Half-Acceptance Angle**
FP200ERT	200	0.5	30º
FG200LEA	200	0.22	12.71º
FG105LCA	105	0.22	12.71º
FG105LVA	105	0.1	5.73º
FG050LGA	50	0.22	12.71º

The results shown in Figures 2 through 6 illustrate the measurements obtained from the proposed optical fiber and photodiode-based radiometer [6] when using different optical fibers as solar radiation collectors (red and blue lines). These measurements are compared to those of the commercial pyrheliometer described in the previous section, which was positioned adjacent to the optical fiber tip (black line). The influence of the core diameter and variations of the spectral irradiance along the day in the radiometric measurements were already addressed in [6] and [7].

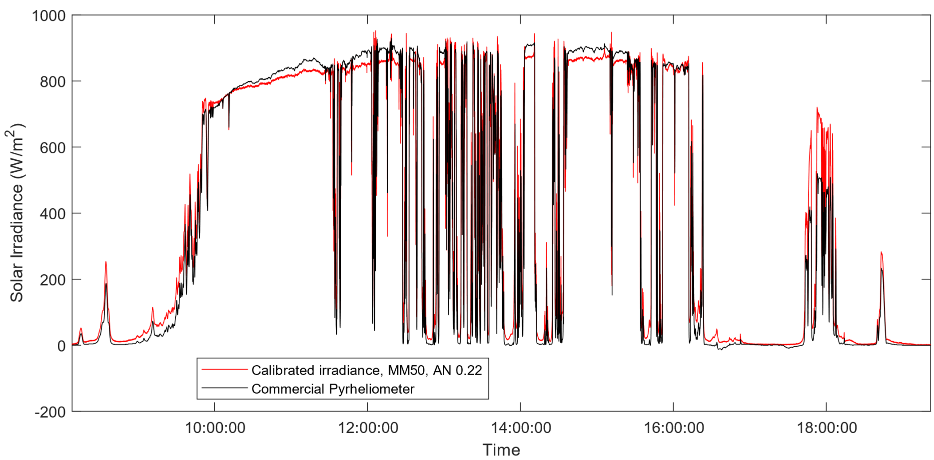

Figure 2. *Solar irradiance measured with THORLABS FG050LGA, with core diameter of 50µm and 0.22 NA during a cloudy day.*

The comparison of results obtained using fibers with different core diameters demonstrates that modifying this parameter does not impact the accuracy of the measurements. The results exhibit approximately the same behavior, as illustrated in Figures 2 and 3, which compare three different core diameters under varying meteorological conditions.

As shown in Figures 2 and 3, the use of an optical fiber as capturing element for solar irradiance measurement is a viable option when being used in the proposed system [6,7], as the results obtained are similar to those from commercial pyrheliometers. The proposed device is not only adequate for sunny days, but also when sky is conditioned by clouds, demonstrating great response time, sensitivity and accuracy.

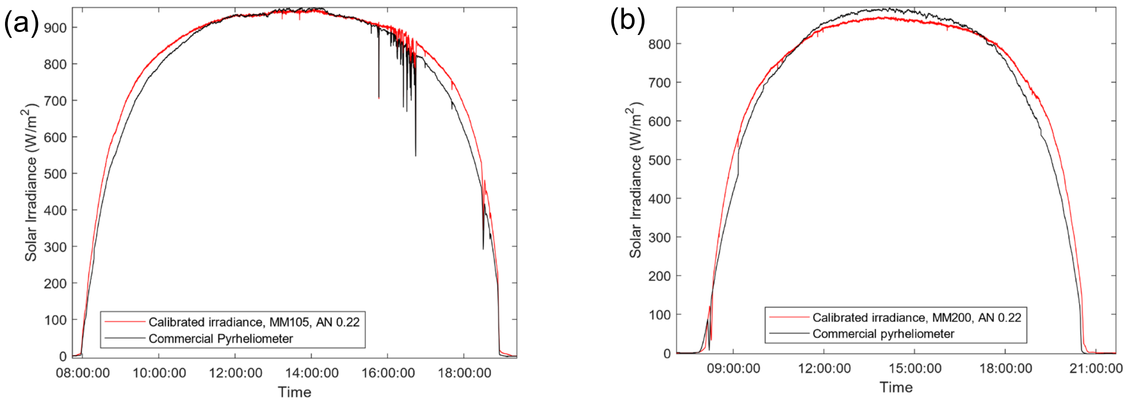

Figure 3. *Solar irradiance measured with (a) THORLABS FG105LCA and (b) THORLABS FG200LEA, with core diameter of 105µm and 200µm, respectively, during two mainly sunny days.*

The primary implications of varying the core diameter of the fibers are related to the ripple observed in solar irradiance measurements. When measuring DNI, as in the application discussed in this article, the power levels involved are relatively low, meaning that the coupled power is close to the photodiode's sensitivity limit. As a result, the ripple has a noticeable impact on the measurements. Using fibers with larger core diameters increases the collected power, thereby reducing the ripple effect. In other radiometric applications where power levels are higher, such as measuring concentrated flux, employing fibers with smaller core diameters could help prevent degradation or even burnout of the optical components.

Although the variations in the core diameter do not have an impact on the accuracy of the results, it presents a challenge when talking about the tolerance on the manufacturing of the optical fiber. According to the specification sheets given by the supplier of the fibers used, the real core diameter has a manufacturing tolerance that goes up to 4%. If this tolerance is combined with the other sources of uncertainty, the instrumental error goes up to 8.6%, computed taking into account the random error introduced by the photodiode. This exceeds the CHP1 sensor's error (3% per hour, 2% per day), but the application of power averaging and introducing an empirical correction factor to overcome manufacturer tolerance could minimize the discrepancy [6].

When discussing numerical aperture, the key conceptual distinction among optical fibers lies in whether the device functions as a pyrheliometer, which depends on its associated field of view. According to the definition of a pyrheliometer and its corresponding standards, the acceptance half-angle of such a device typically ranges from 2.5º to 5º, with some authors suggesting values up to 10º. When using higher numerical apertures, the field of view of the fiber widens; which means that light coupled not only comes from the solar disk, but also from the atmosphere. As will be illustrated, the numerical aperture greatly influences the accuracy of the results.

The results obtained from the THORLABS FP200ERT fiber (shown in Figure 4) have been the less favourable. The numerical aperture associated of 0.5 and an associated half-angle of 30º deviates significantly from the pyrheliometer definition. Thus, the light captured and introduced into the fiber comes not only from the solar disk but also from a large section of the sky, including a significant DHI component in the DNI measurement, which greatly affects the results in some cases. The use of this optical fiber with a numerical aperture of 0.5

on sunny days reveals that the radiation captured from outside the solar disk becomes negligible compared to the radiation coming directly from the sun, as the DHI is much lower than the DNI. Consequently, as seen in Figure 4(a), the results provided by this fiber are similar to previous ones, with relative errors of less than 3% during the central hours of the day.

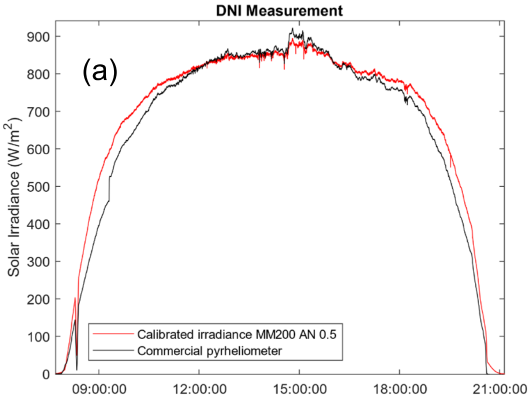

Figure 4. *Solar irradiance measured with THORLABS FP200ERT, with 0.5 NA during (a) a completely sunny day and (b) a cloudy period.*

While on clear skies the DNI is much greater than the DHI, this is not the case when the sky is conditioned by passing clouds or, even less, when the sky is mostly overcast, as displayed in Figure 4(b). In these circumstances, the light coming from the solar disk (which is partially or totally covered) is approximately equal to that coming from the rest of the atmosphere, which is no longer negligible. Therefore, the influence of having a much larger viewing angle between both devices becomes very significant, as the surface area of the atmosphere from which radiation is received is much larger, resulting in DNI values that are very different and higher than those from the commercial pyrheliometer.

The problem observed previously is not unique for the THORLABS FP200ERT with 0.5 NA fiber, but it also is observed on the measurements done with the 0.22 NA fibers. However, the effect is minimized in the new fiber, having a half aperture angle much narrower, of around 12.7º, than in the previous case. In Figure 5, the results comparing the THORLABS FG200LEA fiber (blue line) against the commercial pyrheliometer (black line), and the 0.5 NA THORLABS FP200ERT fiber (red line) presented before are shown. In this case, the results are more consistent, having worse behaviour at clear sky but better when cloudy. In line with the previous comments, although the effect of the DHI on the direct normal irradiance measurement is also observed in this type of fiber, in this case its effect is significantly smaller, meaning that this fiber could act as a pyrheliometer, although the angle defined does not adjust to previous literature [5].

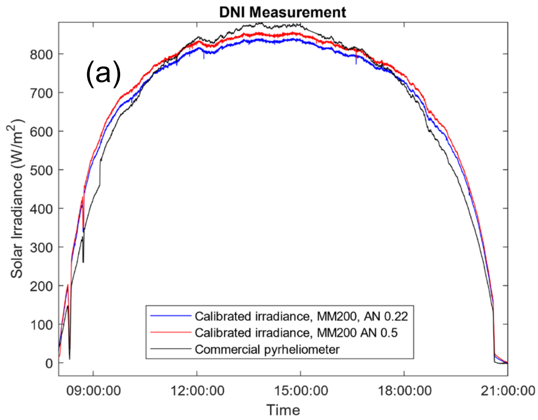

Figure 5. *Solar irradiance measured with THORLABS FG200LEA and THORLABS FP200ERT, with 0.22 and 0.5 NA respectively, during (a) a completely sunny day and (b) a cloudy period.*

Finally, the results related to the THORLABS FG105LVA fiber with a numerical aperture of 0.1 are discussed. For this type of optical fiber, the half-angle aperture is 5.7º, similar to many commercially available pyrheliometers and fits some definitions of pyrheliometers given in the literature, although it does not adjust to the current standards set by ISO and WMO [5]. Figure 6 presents the results acquired with this fiber, where it can be seen that they are approximately equal to the results given by the commercial pyrheliometer, reaching a relative error of less than 1% during central hours of the day. In Figure 6(a) the measurements during a whole day are displayed, while Figure 6(b) presents a period determined by clouds, where the main divergencies were found until now. In this case, the fiber also gives accurate results.

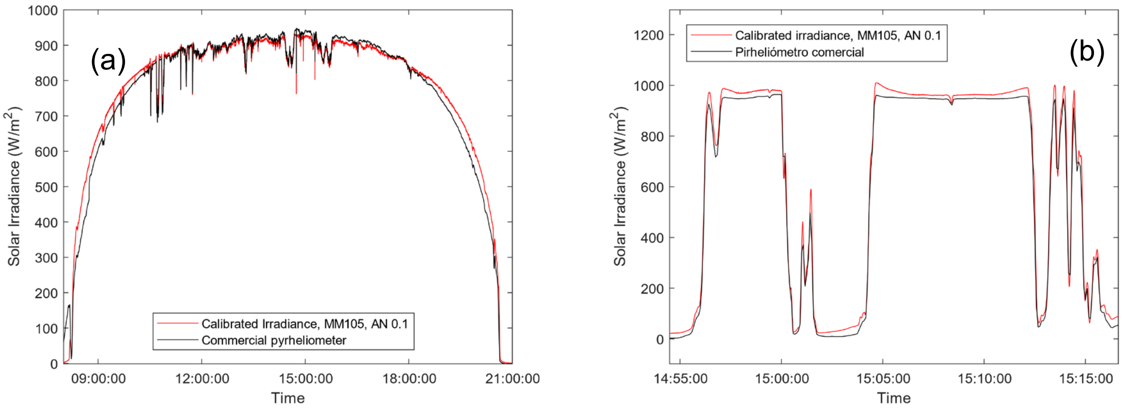

Figure 6. *Solar irradiance measured with THORLABS FG105LVA, with 0.1 NA, during (a) a completely sunny day and (b) a cloudy period.*

4. Conclusions

The study presented demonstrates the feasibility of using optical fibers for radiometric measurements, reaching results comparable to conventional pyrheliometers when using the appropriate numerical aperture for measuring DNI.

Among the different optical fibers used in the different tests, it was proved that the size of the core of the fiber does not affect the accuracy of the device, although it does influence the ripple of the measurements. When varying the different numerical apertures, only the fiber with the smaller field of view (0.1 NA) provided results comparable to the commercial pyrheliometer, while fibers with numerical apertures of 0.22 and 0.5 showed higher errors, especially under cloudy conditions, due to the greater amount of diffuse radiation captured. Eventually, these fibers with greater field of view could be used as solar radiation collectors measuring GHI from a section of the sky, as well as in other applications where the radiation coupled came from a wider angle. In this regard, fiber bundles could also be used, strategically arranging the fibers to cover the entire sky, thus enabling the calculation of GHI.

The use of optical fibers as solar radiation collectors can be a viable and economical alternative for DNI measurement, with potential applications in solar power plant monitoring and meteorological studies. Similarly, the combination of multiple optical fibers with an appropriate arrangement would allow for the measurement of diffuse horizontal or global radiation, although this falls outside the scope of this work. Future research will focus on analyzing the different error sources, such as the tolerance in the manufacturing of the fibers; and a refinement of the calibration algorithm to overcome the variability of the solar spectrum depending on the location, season, meteorology or time of day.

Data availability statement

The data supporting the conclusions reached in this article will be made available by the authors on request to the correspondence email.

Author contributions

Conceptualization, A.C.; methodology A.C.; software M.J.; validation, A.C. and M.J.; formal analysis, A.C.; investigation, A.C., M.J., and J.G.; resources, A.C.; data curation, M.J.; original draft preparation, M.J.; reviewing and editing, A.C. and J.G.; visualization M.J.; project administration A.C. and J.G.; funding acquisition A.C.

Competing interests

The authors declare no competing interests.

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