Remote Optical Powering Using Fiber Optics in Hazardous Environments

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Abstract—Potential niches for a power-over-fiber (PoF) technique can be found in hazardous areas that require controlling unauthorized access to risk areas and integration of multiple sensors, in scenarios avoiding electromagnetic interference, and the presence of ignition factors. This paper develops a PoF system that provides galvanic isolation between two ends of a fiber for remotely powering a proximity sensor as a proof of concept of the proposed technology. We analyze scalability issues for remotely powering multiple sensors in a specific application for the hazardous environment. The maximum number of remote sensors that can be optically powered and the limiting factors are also studied; considering different types of multimode optical fibers, span lengths, and wavelengths. We finally address the fiber mode field diameter effect as a factor that limits the maximum power to be injected into the fiber. This analysis shows the advantages of using step-index versus graded-index fibers.

Index Terms—Graded-index fiber, mode field diameter, multimode optical fiber, power-over-fiber (PoF), sensor networks, step-index fiber.

I. Introduction

A HAZARDOUS area is any three-dimensional space in which a flammable atmosphere can be expected to be present, and requires special precautions of operation. Examples of hazardous areas are: laboratory facilities where flammable liquids are used and stored, flammable solvent printing processes, flammable liquid and gas storage tanks and associated equipment, etc. [1]. Those areas are usually located in industries and specific regulations and standards should be followed to guarantee the highest possible level of safety. However the violation of pictographs of indication of danger safety fences among others, are some of the violations that often end in a lamentable accident. Hence there are solutions in the market focused on: i) access control in industrial environments and ii)

in the sensing and monitoring of hazardous atmospheres. The optical fibers are good candidates to be used in these hazardous environments, because a broken fiber does not produce sparks and they are not chemically affected by most of the substances that react with some metals. They also provide security; it is very difficult to tap a fiber without being detected. The use of optical fiber is already being considered in perimeter monitoring systems based on distributed sensing to cover long distances of tens of km [2], or to provide robust communications among others. Power-over-Fiber (PoF) technology can be a good choice in this scenario if the required sensors and access control systems need to be securely powered, as the optical fiber deployment does not increment the cost. The first work for powering remote loads using optical fibers was reported in 1978, showing the feasibility of the technology to supply energy to an acoustic sensor [3]. PoF systems usually consist of a high-power laser diode (HPLD), a transmission line (an optical fiber), and a converter (i.e., a photovoltaic cell). The evolution of PoF systems has been oriented to improve the performance of all the system elements. Some important advances are: the enhancement of the photovoltaic cell (PV) conversion efficiencies and the transmitted power levels [4], and the use of optical fiber transmission techniques [5] for the integration of power and data through the same channel among others. There are some commercial products available [6] but they can be improved in terms of overall power efficiency, control, dimensions and power levels from medium to long distances.

On the other hand, the use of this technology has diversified into multiple fields such as optically powered remote antenna units [4], [5], [7], [8] or controlled beam steering for Radio over Fiber Networks [9], remote sensor feeding [10] in hazardous environments with high electromagnetic interference (EMI) for measuring the gas density of extra high-voltage substation gas-insulated switchgear [11], for partial discharges monitoring [12] or for current monitoring in transmission lines [13]. Other PoF applications are reviewed in [14], but those specifically within the security sector include the remote feeding of different type of subscribers including a video surveillance system [15]. In most of the sensor scenarios apart from [16], [17], remote powering of a single sensor is considered, and in any case there is no analysis about the scalability of the system and the different factors to simultaneously be considered.

In this paper a PoF system is developed providing all the expected advantages such as the capacity of galvanic isolation between two ends of the fiber, its immunity to EMI and light-
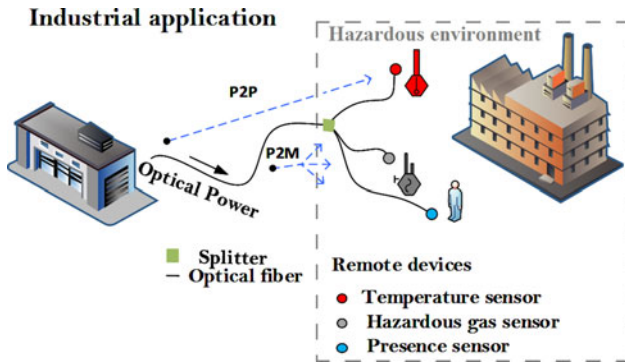
Industrial application

Fig. 1.   Optical powering using fiber optics in hazardous environments. P2P: Point-to-Point; P2M: Point-to-Multipoint.

ning strikes and a proof of concept is provided by remotely powering a proximity sensor to benefit of them. The scalability for remotely powering multiple sensors in a specific application for hazardous environment is also provided. An upper limit of the number of optically powering remote sensors and the limiting factors are also analyzed; considering different types of multimode optical fibers, span lengths and wavelengths.

The document is divided into 4 sections. Section II describes the hazardous environment and the design parameters of the PoF system. In Section III, some design guidance with the developed system, the experimental results and discussions are presented. Finally, Section IV addresses the main conclusions.

II. POWER OVER FIBER IN APPLICATIONS OF SECURITY AND GAS DETECTION

PoF systems can be integrated in sensor networks where fiber-optic based sensing systems or optical communications already exist. Those PoF systems can solve some of the disadvantages of the traditional power supply systems (copper, batteries, harvesting) such as the need for periodic replacement of batteries, or their dependence on fluctuating energy sources such as solar. It is also possible to combine different feeding systems.

On the other hand, the PoF technology allows to supply: i) power via the optical fiber, ii) power on demand adapted to the sensor consumption, iii) data transmission and sensor management, iv) multiple sensors feeding, among others. A possible application scenario that can benefit from these advantages is an industrial environment as the one shown in Fig. 1. Because many factors that can lead to a fire or explosion converge: the presence of fuel and oxygen in certain proportions and the ignition source. These factors are often associated with human errors. Controlling unauthorized access to risk areas can prevent the occurrence of accidents. Fire-retardant characteristics of optical fibers (see standard IEC 60332-1, IEC 60331-25) coupled with adequate measurement of critical variables contribute to minimize the risk.

In this hazardous scenario the sense of several variables is required such as humidity, temperature or hazardous gases together with the integration of a surveillance system. Some examples of those sensors and their average consumption are shown in Table I. They oscillate between tens and hundreds of mW so PoF systems can be used.

TABLE I
POWER CONSUMPTION OF SOME DEVICES

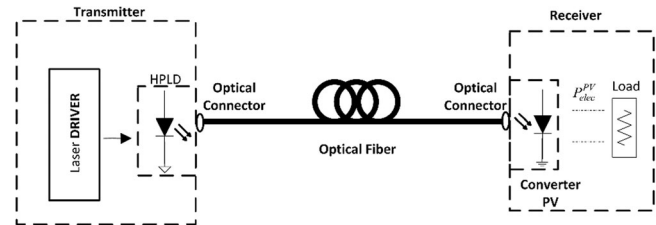| Sensor type	Consumption (W)	Application
AMG88	30mW	Motion detection (temperature)
MP-7217-TC	150mW	Flammable and methane concentration
VQ548MP	297mW (at Power On)	Flammable gas detection

Fig. 2.   Schematic of a generic Power-over-Fiber system.

In most optically powered sensor applications reported to date point-to-point (P2P) topologies are considered and a single sensor is addressed. A tree configuration is described in [17] but not specific analysis of the scalability of the system is carried out, neither in the star topology considered in [16]. In sensor networks with multiple parameters of interest, remotely powering of a large number of sensors is required in different point-to-multipoint (P2M) topologies. If a star topology with a passive splitter is considered, see Fig. 1, all sensors or remote nodes are supplied with the same power. Sometimes the sensors must be placed in specific locations, conditioning the selected topology and span length. It is possible to design the topology with different splitting ratios at each output but using more complex elements.

III. IMPLEMENTATION OF A POWER-OVER-FIBER SYSTEM

A. Design Aspects

A block diagram of a generic PoF system is illustrated in Fig. 2. It shows the HLPD, the optical fiber and the PV. The converter stage transforms the received optical power into electrical power, P_{elec}^{PV}, for driving a load.

The system energy efficiency, SEE, of the power over fiber system can be expressed as [18]:

$$\text{SEE} = \frac{\text{Energy provided to Load}}{\text{Energy provided by HPLD}} \quad (1)$$

And different aspects must be considered in the design:
1) proper match between HPLD wavelength, converter efficiency and optical fiber attenuation,
2) temperature influence on the system performance, especially on HPLD and converter performance,
3) efficiency of optical coupling, the required electronics, and heatsink,
4) maximum power to avoid fiber fuse limitations and passive elements degradation,
5) proper output voltage and electrical power.

TABLE II
MATERIALS, OPERATING WINDOWS AND EFFICIENCIES OF PV CELLS [19], [20]

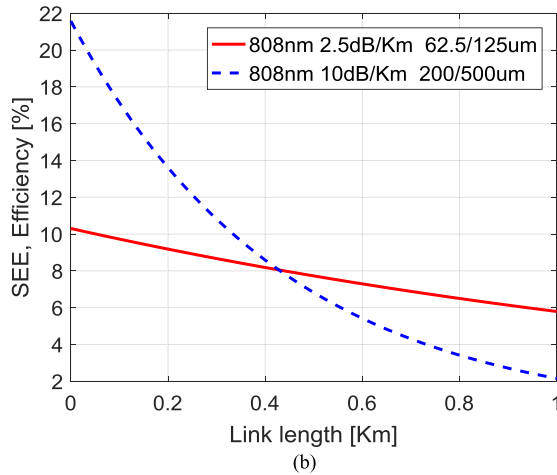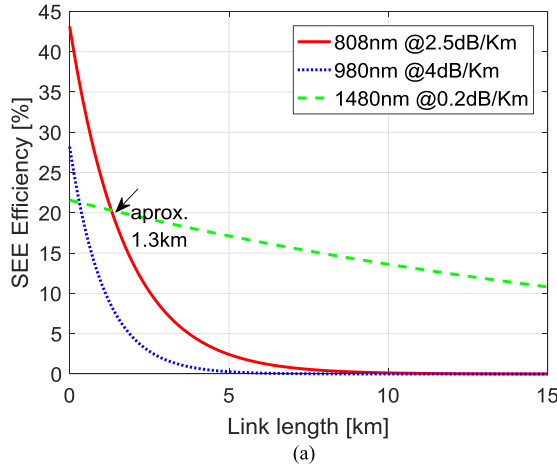| Material	Wavelength range (nm)	Efficiency (%)
GaAs	790 to 850	52%
InGaAs	915 to 980	34%
InP	1400 to 1550	26%

Fig. 3. (a) PoF system energy efficiency, SEE, versus link length for different operating wavelengths. A 100% HPLD-fiber coupling efficiency and PV efficiency of Table II are considered. (b) SEE penalty by the mismatch in the HPLD-fiber coupling efficiency.

The PV efficiencies depend on both the material and the operation wavelength. Table II summarizes the current main three operating windows used by PoF systems.

Some guidelines are shown below regarding the operating wavelength as well as fiber type selection. In Fig. 3(a) SEE is estimated in a point to point link with two connectors with 0.4 dB loss/each and a 100% coupling efficiency from HPLD to the optical fiber as in [7]. The specific parameters are the operating wavelength, the PV efficiency provided in Table II and the related silica optical fiber attenuation in dB/km.

In this first simulation no penalty due to fiber fuse [21], [22] is assumed. The analysis considers the wavelengths commonly used in different applications that have fostered the development of HPLDs available in the market. From Fig. 3(a) is shown that

for silica fibers and link lengths <1.3 km, PV efficiency is the dominant effect and 808 nm is a good choice. Meanwhile for longer distances, optical fiber attenuation starts to be dominant and 1480 nm provides better SEE.

The efficiency of optical coupling can limit the PoF system performance. This optical coupling is estimated by taking into account geometrical, Fresnel and angular losses, respectively [23], [24]. These factors contribute to the fiber coupling efficiency, η, as:

$$\eta = \frac{P_{\text{fiber}}}{P_{\text{source}}} = \eta_{\text{geo}} \times \eta_{\text{Fresnel}} \times \eta_{\text{ang}} \qquad (2)$$

where P_{fiber} and P_{source} are the optical power coupled into the fiber and the optical source power, η_{geo}, η_{Fresnel} and η_{ang} are the terms due to the geometrical, Fresnel and angular losses, respectively.

Fig. 3(b) shows the SEE penalty due to coupling efficiency in case of using an optical fiber with 62.5 μm core diameter and 0.27 NA with respect to a 200 μm 0.22 NA counterpart. For the latter, the HPLD-fiber coupling efficiency is assumed to be 100%, i.e., $\eta = 1$. The same operating wavelength is considered in both cases. This SEE penalty due to the mismatch effect of employing a non-optimized fiber with respect to the optical source reduces the coupling efficiency by 47%. The simulations show that for link lengths up to 430 m the SEE of the PoF system is limited by this coupling efficiency factor, however for longer spans the PoF system is mainly ruled by the optical fiber attenuation.

B. Sensor Network Powering via PoF Means

PoF technique offers a safe power-supply method to sensor networks in hazardous environments as discussed above. Since dedicated optical fiber links may exist between different nodes for sensing and communications, the best is using these links also for power distribution. The number of sensing nodes remotely fed via PoF techniques is closely related to the maximum optical power that can be launched into the fiber, as well as the power consumption of the remote sensing nodes.

There is an extensive body of work on power limits in optical fibers and bulk silica glass [25], [26] however the relative magnitude of the damage threshold for optical fibers is yet to be strictly established. Nevertheless, from experimental observations, there is a wide consensus that the maximum power density, i.e., threshold power density I_{th}, of silica fibers is typically of one to several MW/cm^2 [27], [28]. For our study we consider the 2.5 MW/cm^2 similar to that of reported by Dianov et al. [29]. The maximum power level, P_{th}, depends on the fiber mode field diameter (MFD) that determines the fiber effective mode area (A_{eff}). In a multimode fiber, and assuming a Gaussian power distribution entering the fiber, the analysis of the effective area of the fundamental mode provides an upper bound condition to the threshold power to avoid fiber damage. This maximum power is given by:

$$P_{\text{th}} = A_{\text{eff}} I_{\text{th}} = \pi \left(\frac{d_{\text{MFD}}}{2} \right)^2 I_{\text{th}} \qquad (3)$$
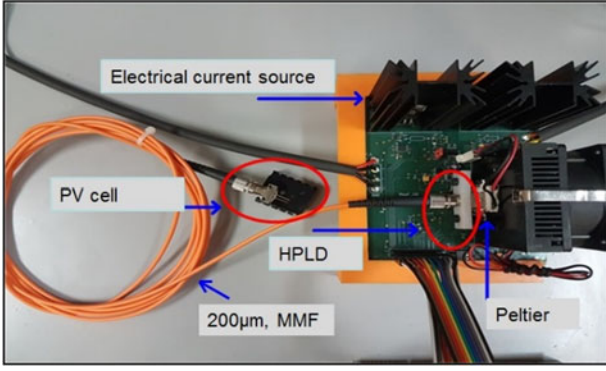
Fig. 4. Prototype of the developed PoF system, based on a 200 μm core diameter silica multimode optical fiber.

being A_{eff} the effective area of the fundamental mode and d_{MFD} the fiber mode field diameter using the near-field Gaussian approximation of the intensity distribution.

The maximum number of sensors, N or N_{sens}, in a P2M start topology is given by:

$$N_{\mathrm{sens}} = 10^{\left[\frac{P_{in\_\max} - P_{\mathrm{Rx}} - \alpha_{\mathrm{fiber}} \cdot L_{\mathrm{fiber}} - \alpha_{\mathrm{con}} \cdot N_{\mathrm{con}} - EL_{1\mathrm{xN}}}{10}\right]} \quad (4)$$

where $P_{in\_\max}$ is the maximum allowable optical power in dBm ((P_{th} in (3)), P_{Rx} is the optical power provided to the PV in dBm, α_{fiber} is the optical fiber attenuation in dB/km, L_{fiber} is the fiber length in km, α_{con} is the connector loss in dB, N_{con} is the number of connectors, and $EL_{1\mathrm{xN}}$ yields for the excess loss of the 1 x N splitter in dB, respectively.

The optical power provided to the PV should fulfill the electrical power demanded by the sensor, so:

$$P_{\mathrm{Rx}}\,(\mathrm{dBm}) = 10 \cdot \log\left(\frac{P_{\mathrm{PVcell}}\,(\mathrm{mW})}{\eta_{\mathrm{cell}}}\right) \quad (5)$$

where P_{PVcell} is the electrical power consumed by the sensor with the highest consumption, and η_{cell} is the PV efficiency.

The available power for feeding each sensor in a P2M topology is N times lower than in the case of using the P2P topology. It is also possible to analyze the system using a bus topology, but in that case, more passive elements are required and the coupling ratio in each division must be adjusted for maintaining the same available power for each sensor [30].

C. PoF System Setup

We have developed specific prototypes providing an optical remote powering fiber channel of hundreds of mW in DC and pulse mode operation for different types of multimode silica and polymer optical fibers [31], [32]. One of those prototypes is shown in Fig. 4.

The system includes a HPLD of 1.5 W at 2.2 A with a central wavelength of 808 nm and a GaAs PV. The HPLD and the PV are connected via a 200 μm core diameter silica optical fiber. The designed laser driver provides a slow start and a current limit to protect the laser. Fig. 5(a) shows a simplified electrical schematic of the laser driver, including an adjustable regulator (the integrated circuit LTC3083) used to provide a variable current source controlled by the Rvar resistor. The slow
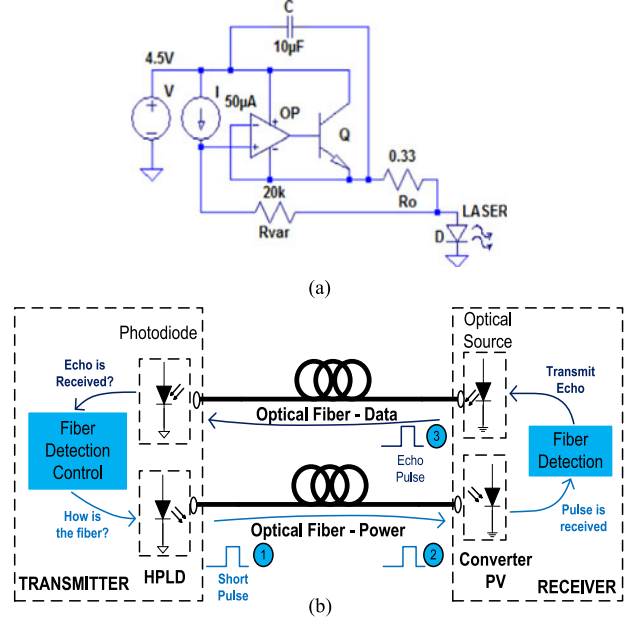

Fig. 5. (a) Simplified electrical diagram of the HPLD driver. (b) PoF system with fiber detection scheme.

start is controlled by charging a capacitor (not shown in the figure). It also performs a temperature and a current control loop system to stabilize the output optical power. A Peltier element is used to keep the temperature of the HPLD at 25 °C $\pm$ 0.01%.

As previously stated, hazardous environments require safety operating conditions and the PoF system works at high optical powers. A specific protection mechanism is developed to detect if the fiber is connected previously to drive ON the HPLD. This protection aims to (i) prevent the HPLD from becoming a source of ignition itself or causing damage to the operator and (ii) detect changes in the link, e.g., attenuation. The mechanism consists of the transmission of a short duration pulse by the feeding power optical fiber as part of the power-up process. The receiver replicates this hardware pulse (echo) sending it back to the transmitter via the optical fiber dedicated to send the data [see Fig. 5(b)]. There are two blocks, one based on firmware and hardware in the transmitter and the other one based only on hardware in the receiver. The transmitter uses the HPLD to generate the pulse but operating around its threshold current. The echo pulse is detected by an amplifier with more than 70 dB gain factor, and it is acquired by the 12-bit digital-to-analog converter of the microcontroller for validation. The amplitude of the amplified pulse is in the range of tens to hundreds of mV, depending on the PoF system. The transmitted and eco pulses can be seen in Fig. 6. The receiver only uses hardware to replicate the pulse since the execution of firmware requires additional undesired power consumption. The echo pulse amplitude can be used to estimate the link losses.

D. PoF System Experiments and Results

Table III summarizes the set of experimental trials using the PoF system described in Section III. They have been performed with different multimode optical fibers: i) silica Step-Index (SI),
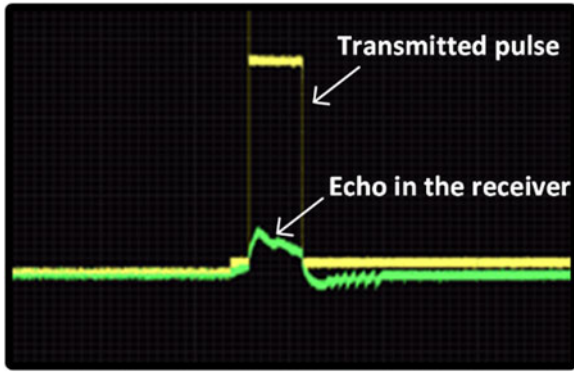
Fig. 6.   Transmitted and received pulses from the fiber detection scheme.

TABLE III
MEASUREMENTS OF ELECTRICAL POWER DELIVERED AT THE REMOTE
(SENSING) NODE

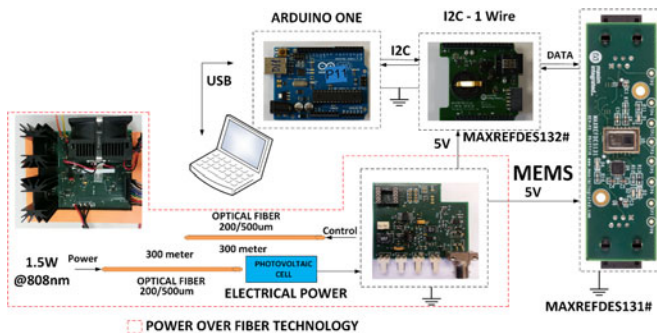| Fiber type (Core/cladding dimeter, μm)	Link length (m)	Electrical power delivered (mW)
GI-silica (62.5/125μm)	1	240
SI-silica (200/500μm)	1	409
SI-silica (200/500μm)	300	360
SI-POF (980/1000μm) [28]	2.5	197

Fig. 7.   Implementation of the PoF system to remotely optically fed a proximity sensor with logic control.

ii) silica Graded-Index (GI), and iii) SI polymer optical fiber. The nodes are fed with low and medium powers at distances of hundreds of meters for silica fibers.

As a proof of concept we tested our PoF system for powering a proximity sensor using MEMS-based thermal sensing technology, see Fig. 7. We employed an AMG88 infrared array of sensors that provide an 8×8 matrix (64 pixels) of thermal microsensors within the same package. It allows the detection of body radiation and other objects up to 7 m. Both the Arduino and I2C-1 Wire modules only serve for logic control purpose of the sensor and data acquisition. The PoF system employs two 300 m-long 200/500 μm core/cladding diameter optical fibers. One fiber is used for remote optical powering purposes whereas the other fiber is employed to provide control information to the transmitter thus enabling a remote smart monitoring of the system. The control link bit-rate is 30 Kb/s.

Although in the experiment only a single sensor is fed we estimate from (4) that up to 5 sensors could be fed within a
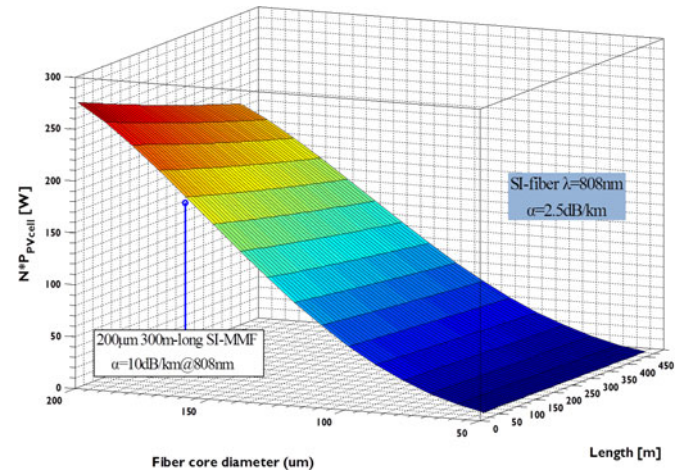

Fig. 8.   Figure of merit versus fiber length and core diameter. Blue dot: $N \times P_{\mathrm{PVcell}} = 138$ W for a 200 μm core diameter and 300 m-long SI fiber.

perimeter of 300 m. For this estimation we have assumed a fiber with 10 dB/km at 808 nm, a 100% HPLD-fiber coupling efficiency, 1 dB penalty due to fiber connectors throughout the link, a 1×2 optical splitter with 0.5 dB excess loss, and the maximum power recommended by the fiber manufacturer [33]. Special care is taken to avoid dangers of heat accumulation linked to high optical power concentration at the HPLD and the receiver [34] and to connector dirt.

E. Discussion

The recent advances in power-efficient innovative hardware, low-energy medium access control protocol and power consumption savings in electronics boost the niche market of optically powered remote smart sensor networks via PoF means.

Beyond PoF applications that involve only a dedicated optical fiber for a specific sensing device, this section focuses in P2M topologies. We analyze the feasibility of optically powering smart sensor networks in a centralized fashion. Coverage distances of interest have been considered up to around 450 m. The number of nodes and their power consumption, the link length and the maximum optical power into the fiber are parameters that determine the PoF system performance. The scalability is analyzed through the definition of the figure of merit $N \times P_{\mathrm{PVcell}}$, being N and P_{PVcell} the number of optically powered sensors and the value of the greatest power consumption between all nodes involved within the P2M sensor network topology. Fig. 8 depicts the influence of the link length and fiber core diameter on the figure of merit $N \times P_{\mathrm{PVcell}}$. A SI silica optical fiber with 2.5 dB/km at 808 nm is considered. The total optical power launched into the PoF system, P_{th}, to be distributed among the N sensors is computed from (3). In our simulation we assume a fiber threshold power density close to the theoretical limit $I_{\mathrm{th}} = 2.5$ MW/cm^2 and an effective area determined just by the fiber core diameter. 100% HPLD-fiber coupling and 52% PV efficiency are considered. 1 dB penalty due to fiber connectors throughout the link and 0.5 dB excess loss from a (generic) $1 \times N$ optical splitter are also assumed to emulate a real-case scenario for PoF distribution. Theoretical results show, for instance, that
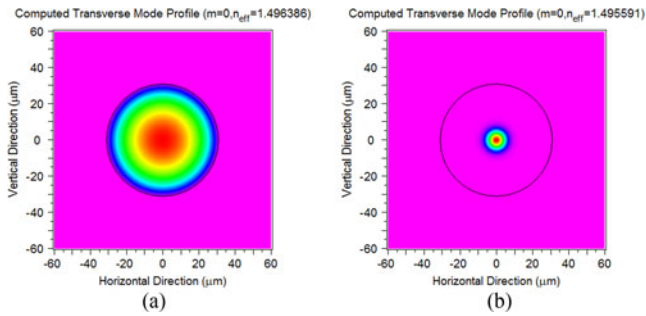
Fig. 9. Field distribution of the fundamental mode at 808 nm for different multimode 62.5/125 μm core/cladding diameters silica fibers: (a) SI and (b) GI.
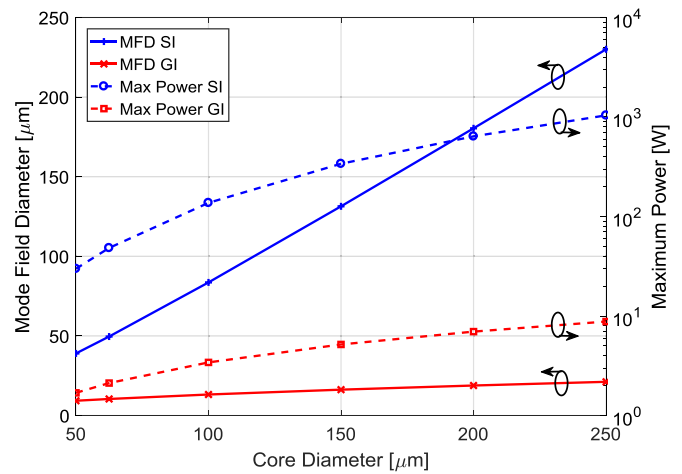

Fig. 10. Influence of the Mode Field Diameter (MFD) on the maximum allowable optical power injected into a SI- and a GI-fiber, and for different fiber core diameters.

a 100 μm core diameter 100 m-long PoF system provides a $N \times P_{\mathrm{PVcell}}$ figure of merit of 57 W. This means that 5700 sensors could be remotely powered via PoF if the maximum power consumption per node is lower than 10 mW and enough power is available. Blue dot in Fig. 8 represents the expected results obtained from another optical fiber with 10 dB/km at 808 nm 200 μm core diameter 300 m-long SI silica optical fiber (as the one reported in Table III). In this case, the PoF system shows a $N \times P_{\mathrm{PVcell}}$ factor of 138 W.

Optical fiber damage threshold is application dependent. A good rule of thumb is to keep the energy density around four-to-six times smaller than the upper limit I_{th} of expected damage threshold [25], [33]. Fig. 8 results can be consequently scaled by this design consideration. For instance, if considering a power density I $= 250\,\mathrm{kW/cm^2}$, one order of magnitude lower to the $I_{\mathrm{th}} = 2.5\,\mathrm{MW/cm^2}$, the number of optically powered remote nodes is accordingly scaled.

As stated before, the mode field diameter (MFD) play an important role in determining the maximum optical power into an optical fiber. The influence of refractive index profile in the MFD is analyzed in [35] using approximated equations. In this work, a Finite Difference Beam Propagation Method, BeamProp from Rsoft software, is used for calculating the fundamental mode profile of two 62.5 μm core diameter optical fibers at 808 nm (see Fig. 9).

MFD is calculated to estimate the maximum allowable optical power in each type of optical fiber using (3). Both MFD calculations and maximum allowable optical power for each optical fiber are depicted in Fig. 10. From Fig. 10 we can observe that the rate of MFD increment with core diameter is greater in SI versus GI optical fibers. Therefore the maximum allowable optical power increases exponentially with the core diameter for SI fibers. Normally, doubling the fiber core diameter should allow one to apply a fourfold input power value until damage occurs. On the contrary, the variation of the MFD of GI optical fiber is lower. The maximum allowable optical power changes from 1.69 W for a 50 μm core diameter to 8.79 W for a 200 μm core diameter optical fiber, only around eight times instead of more than thirty times as it happens in the SI optical fiber.

If we consider the case of using a 200 μm core diameter 300 m–long optical fiber with 2.5 dB/km at 808 nm, the $N \times P_{\mathrm{PVcell}}$ factor of 232 W obtained for a SI fiber is reduced almost to 3 W,

i.e., two orders of magnitude below, if a GI optical fiber with the same core diameter is used.

Finally, the availability of HPLD impacts on PoF systems. Their evolution for medical applications, pumping and fiber lasers will be relevant on the development of PoF in the future.

IV. CONCLUSION

Hazardous environments are intrinsic market niches for Power-over-Fiber (PoF) systems that may benefit from their expected advantages such as galvanic isolation between two fiber ends, intrinsically safe nature, EMI immunity and powering on demand multiple sensors. In this work, the scalability of the use of the PoF technique and its limitations to remote sensor network topologies has been discussed. We have developed specific PoF prototypes providing optical remote powering of hundreds of mW in DC and pulse mode for different types of multi-mode fibers. Those prototypes include protection mechanisms to prevent ignition and are used to remotely powering proximity sensors as part of a surveillance system in hazardous areas.

We have demonstrated that, beyond inherent limitations due to the multimode fiber type, span lengths and operating wavelengths considered, one should pay special attention to the mode field diameter, i.e., the power distribution across the end face of the fiber, as a limiting factor that dramatically affects a good PoF scalable design.

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