Technology update on patent and development trend of power over fiber: a critical review and future prospects

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Abstract. Conventional electricity distribution using copper wires is well established due to its high efficiency. However, recent research and development on power-over-fiber (PoF) has proposed optical fiber as an alternative to copper wire as the transmission medium for electricity distribution. The research and development on PoF technology have gained significant momentum over the past decade due to its advantage over copper cables in providing electrical isolation and reducing space in remote sites. The technological advances in laser diodes, fiber optic cable fabrications, and semiconductor manufacturing contribute to developing an efficient PoF system, making them more commercially viable. This paper reviews various PoF systems that imply different arrangements of high-power lasers, fiber optic cables, and photovoltaic power converters. The PoF systems are made available for various applications such as in-home applications, smart power management, and powering sensors with bidirectional communications. The comparison of the PoF composition, commercialized PoF systems, and patented PoF systems are also comprehensively discussed. Finally, the challenges in implementing PoF systems are highlighted, as well as future prospects for research and applications. The information reviewed in this paper aims to provide a roadmap for developing a future PoF system with improved power conversion efficiency. © 2023 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JPE.13.011001]

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1 Introduction

Power-over-fiber (PoF) is not a relatively new term in photonics and has been studied since the 1970s. PoF, at its core, is a system in which a high-power laser source transmits a few watts of optical power on a single mode (SMF) or a multimode fiber (MMF). A photovoltaic (PV) converter converts the optical power into electrical power at the receiving end. The system has been studied in various applications such as Internet of Things (IoT), optical powering of remote antenna units, sensor monitoring systems, submarines, video camera systems, and high voltage applications. PoF is also found to be a safer alternative in distributing power using optical fiber. Comparatively, copper wire possesses a much higher power transmission efficiency at more than 98% and it has the capacity of carrying high power, hence it is extensively used as a medium in transferring electrical power. However, optical fibers are preferable due to their robustness to electromagnetic interference (EMI), short circuit, and sparks. The fibers’ immunity to EMI is due to the fact that no radiation is emitted to cause an interference. Optical fibers are also less bulky, capable of operating over long distances, and impervious to moisture and corrosion.
PoF systems provide several more benefits compared with conventional power transmission. Implementing the PoF system is able to improve the provision of power supply to harsh industrial environment, hazardous areas, and extreme weather. PoF is also an alternative to the batteries and long copper cables typically used in remote places. Moreover, optical fiber cable installation has minimal security risk in the power distribution system and is less susceptible to explosive and harsh industrial environment. This is because optical fiber only transmits light, which can avoid fire hazard and electric shock from a broken fiber. In addition, the fiber is safe from all kinds of virtual interferences such as lightning and corrosive area. In terms of data transmission, PoF has a larger bandwidth and can transmit higher volumes of data compared with copper cables. A single optical fiber that can simultaneously carry data signals for sensors and telecommunications is considered to be more advantageous.

The existing review papers on PoF have discussed replacing copper cables with fiber optic cables in critical applications such as powering data link and relay antennas. Although the analysis from the review papers has given a better understanding of applications of PoF through the various advancements within the years of studies up to 2021, there are still certain studies that were not analyzed, such as inability to transmit power over long distances, high cost, and low overall optical to electrical conversion efficiency. Furthermore, there was a lack of analysis on the ongoing research and development surrounding PoF systems, which will be dissected in this paper.

Research on PoF systems has received extensive attention especially in the past decade due to the vast range of applications that can implement the usage of the system. Matsuura studied the papers that were presented in 2019 to 2021, solely focusing on experimental results while in another paper, types of fibers especially double-clad fibers were discussed, introducing the PoF system to power remote antennae units (RAUs) in mobile applications. In another study by Rosolem, the PoF concept was analyzed in regards to access networks and smart grid developments. However, the research work has been limited to certain applications and not PoF system as a whole. Currently, there is no critical review and discussion on the technology update on the patent and development trend of PoF. Therefore, this review aims to fill in the gap by providing an in-depth analysis of PoF system.

This paper aims to summarize the research and development aspects of PoF systems such as the overview and advancement of the PoF system, parameters of laser diode (LD), types of optical fibers, and PPC materials. In addition, this paper provides a detailed analysis of PoF experimental setups and their output performances, applications, and patented PoF. The paper concludes with recommendations of different criteria needed to choose PoF components, mitigation actions to reduce loss in power transmission, and the prospects for future PoF applications.

2 PoF System Overview

Figure 1 shows the overview of the system. Essentially, a PoF system consists of a transmitter, optical fiber, and receiver. The transmitter unit consists of a laser source that acts as the light source for PoF systems and thermo-electric cooler (TEC) controller that does the electrical-optical conversion. The optical fiber functions as the medium of transmission and there are several types of optical fiber such as MMF, SMF, and double-clad fiber (DCF). At the end of the system, the receiver unit consisting of a PPC and DC-DC converter, converts optical energy to electrical energy that will be supplied to an electrical load. The basic concept of PoF mechanism demonstrates that the optical energy from a high-power laser is transmitted via optical fiber and then converted into electrical energy by a PPC on the other end of the fiber. The crucial concern for a PoF mechanism is to transmit and supply the optimum power efficiency to a load at a maximum distance with the highest overall performance. The amount of power that the PoF mechanism can deliver is generally governed by its main components, which are laser, fiber, and PPC. The parameters that influence the amount of power produced by the PoF system are optical power output from laser, the maximum transmitted optical power in the optical fiber, optical power input to the PPC, the power loss of the fiber over optical connectors and distance of connection, and efficiency of laser, fiber and PPC.
A previous study discussed the relationship between the efficiency of LDs in electrical-to-optical conversion to the ratio of optimized bandgap to voltage, \( E_g / V \), efficiency of current injection, \( \eta_i \), external differential quantum efficiency, \( \eta_d \), and the threshold current, \( I_{th} \). LDs with different materials and wavelength operations can have different sets of these parameters. The approximate representation of the electrical-to-optical conversion efficiency, \( \eta_{eff (LD)} \), is described as follows:

\[
\eta_{eff (LD)} = \eta_i \eta_d \frac{E_g}{V} \left(1 - \frac{I_{th}}{I} \right). \tag{1}
\]

In the optical transmission part, the optical power transmitted throughout the optical fiber follows Lambert’s Law, which states that attenuation depends on the material length, and most commercial optical fibers have attenuation losses that are expressed in dB/km. The attenuation losses in dB/km \( \rho_{dB/km} \), are expressed in terms of the amount of input light, \( \alpha_{in} \), and the amount of output light, \( \alpha_{out} \), in:

\[
\rho_{dB/km} = 10 \log_{10} \left( \frac{\alpha_{in}}{\alpha_{out}} \right). \tag{2}
\]

Most power losses in the optical-electrical conversion part occur in the PPC. It was explained in past work that the conversion efficiency of PPC, \( \eta_{eff (PPC)} \), depends on the density of current at maximum output power, \( J_m \); the voltage at maximum output power, \( V_m \); and the optical intensity, \( L_{int} \). Similar to the LDs, these parameters in PPC are related to the material of the PPC. The equation that describes the relationship between the parameters is shown as:

\[
\eta_{eff (PPC)} = \frac{J_m V_m}{L_{int}}. \tag{3}
\]

### 2.1 Laser Diode

An LD is a semiconductor laser that is electrically pumped. A portion of the energy produced by the recombination of electrons and holes in the active region is released as photons. An LD behaves like mirrors with variable reflectivity when its end facets are coated or uncoated, producing an effective laser resonator. The feedback and ultimate gain of the radiation’s stimulated emission are advantageous to an LD. Besides that, LDs offer a wide range of wavelengths, ranging from ultraviolet (UV) to infrared (IR). LDs produce a stream of coherent and highly directional photons compared with another light source such as LED, which produces incoherent light that typically has a vast divergence.
In the PoF system, LDs act as an optical power transmitter, which is usually driven by a laser controller and coupled with an optical fiber. LD provides the most effective high-power supply of photons in converting electric power to optical power, generating optical conversion efficiency between 30% and 70%. This was demonstrated by Peters et al. in 2007 where high power 940 nm LDs with up to 76% electrical-to-optical power conversion efficiency. In addition, LDs provide more wavelength options in the PoF system spectrum, ranging from 780 to 1650 nm for connection with optical fiber compared with any other light sources such as LED. Additionally, fiber lasers are also used as a light source; however, degradation of the cladding caused by high power or the power stability remains unsolved an issue.

Other than that, the power of LDs is dependent on the wavelength choices of the laser. The operating temperatures of the laser are preferably monitored during full power operation of the laser. ATEC is used to keep a constant LD temperature in operation at 25°C. Temperature control is important to maintain the operating lifetime of the LD by protecting it from thermal aging. On another note, passive cooling can be engineered into the PoF system. Since thermal energy is transported conductively from a copper heat sink to the system baseplate without the use of a cooling liquid, passive cooling is less expensive and difficult. It is better to use passive cooling to reduce system costs.

In terms of the wavelength, the semiconductor used as the active medium determines the operating wavelength of an LD. A suitable wavelength of the LD is required to improve the efficiency of the PoF systems. The most used wavelength in past research was 808 to 840 nm. This is because 808 nm is a suitable wavelength for minimal optical fiber loss for a transmission distance that is <1.3 km. While the optical fiber cables that have the distance of <1.3 km should use 808 to 840 nm, it has been recorded that a wavelength of 1480 nm should be used for optical fiber cables with longer distance to provide better efficiency of the PoF system.

### 2.2 Optical Fiber

The optical power produced by LDs is transmitted through an optical fiber. The light signals produced by LDs at one end of the cable are transmitted across the fiber optic backbone and reflected to the core as the light reaches the fiber optic cladding, thus preserving the light inside the core. SMF and MMF are two types of optical fiber cables that are commonly used. SMF has a small inner core (9/10 μm), which has only one direction of light and the MMF contains a larger inner core (50/62.5 μm). MMF has a greater core diameter than SMF. Therefore, it has more than one transmission mode. In comparison, MMF is typically used for short-distance transmission, whereas SMF is used for longer distances. SMF has smaller core regions resulting in smaller optical power transfer, which is not ideal for high power distribution. Although MMF has a larger core area compared with SMF, the disadvantage is that the transmission speed of the MMF is being delayed by the large core area and eventually leading to modal dispersion.

In addition, the interference between optical power and transmission data arises in the same core. Another type of fiber that has potential and is being used in recent research to achieve higher power is DCF. To maximize the optical power of SMF, DCF has been made to transfer high power via the cladding of SMF fiber. DCF contains a small single-mode core and large inner cladding that wraps the single-mode core. Therefore the laser light will propagate in a single-mode core surrounded by an inner cladding with a large core effective area over 240 times larger than that of the SMF core. Consequently, unlike SMF and MMF, DCF is chosen for high optical power and simultaneously transmits optical data. There is also step-index plastic optical fiber (SI-POF) that has been recently used to integrate PoF in home networks with a data transmission speed of up to multiple Gbit/s. The experiments showed that several mW of optical power could be delivered without significantly degrading the signal quality and only produced $1 \times 10^{-10}$ bit error ratio. While various types of optical fiber cables are available, different types are selected based on the required applications. Table 1 summarizes the specifications of SMF, MMF, DCF, and SI-POF cables. The highest transmission distance was reported by López-Cordona et al. The PoF system was transmitted through SMF optic cable over 14.43 km with an optical loss of 3.89 dB.
2.3 Photovoltaic Power Converter

The receiver unit hosts PV cells where the optical power is converted to electrical power to supply the load. The most common semiconductor materials used are Gallium Arsenide (GaAs), Indium Gallium Arsenide (InGaAs), Gallium Antimonide (GaSb), and Silicon (Si). The conversion efficiency and the maximum electrical power output are the most important indicators of PV cell performance. There are also significant differences in energy gap and open-circuit voltage ($V_{oc}$) between these materials, which affect the minimum electrical energy required for the semiconductors to conduct electricity. The energy gap of GaAs material is 1.4 eV and produces 1.1 V of output voltage, and Si material has 1.12 eV with 0.7 V of output voltage level, which are lower than those of GaAs. InGaAs and GaSb have the same energy gap and the output voltage level of 0.7 eV and 0.5 V, respectively. The efficiency of these materials for PoF mechanism in different experiments were reported; Si has a maximum efficiency of 42.9% at 980 nm, whereas InGaAs and GaSb have 45% and 49% peak efficiency at 1550 nm and 1680 nm, respectively. GaAs is a good material for PV since it has a direct and large bandgap material and has high tolerance over a wide range of temperatures. GaAs PPC was reported to possess a maximum efficiency of more than 60% at 800-850 nm range and another paper by Helmers et al. reported a conversion efficiency of 68.9% for GaAs-based power converter under 858 nm monochromatic light. In another study by Fafard et al., it was demonstrated that GaAs-based laser power converters at 808 nm at 150 K were found to have a conversion efficiency of 74.7% and 68.9% at a laser illumination of 858 nm in another research. The main limitation of GaAs is that it has a minimal spectral response. However, the transmission wavelength at 850 nm is still in the first minima attenuation window. To increase the efficiency of a GaAs PPC, it was reported that a heterostructure architecture can increase conversion efficiency up to 65% and allows for applications with larger output powers and new wavelengths. For InGaAs PPC, the highest performance is shown by heterojunction solar cell, which can be implemented in the application of PPC. The significance of high PPC efficiency was demonstrated in applications such as photonic boost converter and optically-isolated DC supply.

Table 2 shows the measured performance of common PPC such as Si, GaAs, and InGaAs for high-intensity laser application in terms of open-circuit voltage, energy gap, bandgap type,
sensitivity, operating wavelength, quantum efficiency, and conversion efficiency. The conversion efficiency is defined as how much electrical power can be produced for every 1 W of optical power. Based on the table below, Si’s indirect band gap makes it a less than perfect optical material. However, Si can still be a promising material for PPC applications, with a conversion efficiency of up to 40% at 850 nm wavelength, and apparently has low manufacturing cost. Besides that, different efficiency levels for GaAs cells have been reported mostly due to GaAs-based power converters’ output voltage can be increased by interconnecting converter segments or multijunction PV cells. While InGaAs and GaSb have output voltage levels lower than GaAs, 0.5 V, which is too low to supply power to any devices. These materials are not an option for the high performance of PoF systems. However, GaSb converters may benefit wireless applications since it has been used as a material to develop high-intensity laser power beaming that can be used for wireless power transmission. InGaAs is reported effective at 1550 nm while GaSb at 1315 nm. Another study reported that PPCs made of InGaAs materials have the capacity to transmit electrical energy over several kilometers. Fafard and Mason also demonstrated in their research that InGaAs/InP PPCs for 1470 nm may generate electrical output voltages of more than 4 to 5 V indicating the capability of long-wavelength converter. At 1520 nm InGaAs PPC, it was found that the maximum room temperature conversion efficiency was 36.9%. In most cases, PPC contributes most of the power loss in the PoF system since they do not generally have high conversion efficiency. A study on PPC material found that high bandgap material such as ZnS and 6H–SiC with bandgaps of 3.54 and 3 eV, respectively,.

### Table 2 Measured PV cell performances for high-intensity laser application according to material type, open circuit voltage, energy gap, bandgap type, sensitive wavelength, and experimental results of conversion efficiency.

<table>
<thead>
<tr>
<th>Semiconductor material</th>
<th>Open circuit voltage (V)</th>
<th>Energy gap (eV)</th>
<th>Band gap type</th>
<th>Sensitive wavelength (nm)</th>
<th>Experimental results of conversion efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon (Si)</td>
<td>0.59 (808 nm)</td>
<td>1.12</td>
<td>Indirect</td>
<td>800–1000</td>
<td>24.70</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3064,65</td>
</tr>
<tr>
<td>Gallium arsenide (GaAs)</td>
<td>1.05 (808 nm)</td>
<td>1.42</td>
<td>Direct</td>
<td>790–850</td>
<td>32.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>800–900</td>
<td>4069</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>780–980</td>
<td>4168</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>5268</td>
<td></td>
</tr>
<tr>
<td>Indium gallium arsenide(InGaAs)</td>
<td>0.48 (1480 nm)</td>
<td>0.83</td>
<td>Direct</td>
<td>1300–1600</td>
<td>22.20</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>256</td>
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<td>3467</td>
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<td></td>
<td></td>
<td>4567</td>
</tr>
<tr>
<td>Gallium antimonide (GaSb)</td>
<td>0.5 (1315 nm)</td>
<td>0.73</td>
<td>Direct</td>
<td>—</td>
<td>4067</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>—</td>
<td>4955</td>
</tr>
<tr>
<td>Aluminium gallium arsenide (AlGaAs)</td>
<td>1.26 (820 nm)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>5655</td>
</tr>
<tr>
<td>Indium phosphide (InP)</td>
<td>—</td>
<td>1.35</td>
<td>—</td>
<td>1300–1550</td>
<td>24.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2668</td>
</tr>
<tr>
<td>Germanium (Ge)</td>
<td>0.22 (1480 nm)</td>
<td>0.66</td>
<td>—</td>
<td>1300–1600</td>
<td>9.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30.4</td>
</tr>
</tbody>
</table>
contributed to a higher efficiency. However, the doping limitation remains a major challenge that would have to be addressed. Hence, each PPC has disadvantages and limitations that rely more on wavelength and materials. For example, GaAs PPCs have high efficiency, voltage per cell (>1 V), whereas Si PPCs are advantageous in terms of having a mature planar technology. InGaAs and GaSb, on the other hand, have a very low fiber attenuation compared with GaAs.

2.4 Performance Improvements of PoF System

The efficiency of PoF systems can be improved by considering the specifications of the transmitter, optical fiber, and receiver in the PoF system. The main component of the transmitter unit is the LD, which is used to convert the electrical power to optical power and transmit to optical fiber. The limitation of optical fiber is a maximum power limit that can be used for a PoF system. This is due to the fiber-fuse effect, resulting in heat increases in the optical fiber. It is stated that the limitation power at 1467 nm for SMF is 1.5 W, and SMF with type 28 F is 1.0 W. On the other hand, it is recorded that the maximum power of MMF at 1060 nm is 4.0 W.

The main component of the receiver unit is the PPC, which transforms the optical power to electrical power and delivers it to electronic devices. The maximum electrical power output and PV conversion efficiency are two of the most important limitations at the receiver unit. Among the PV cell listed in Table 2, the GaAs PV cell is reported to be the most commonly used PV cell with conversion efficiencies of 51% to 54%. Most experiments choose GaAs, due to their better responsivity to shorter wavelengths and high-temperature resistance. It can be concluded that the overall efficiency of PoF systems can be optimized if the suitable LD, optical fiber, and receiver are selected in an experiment. However, the efficiency of the overall system may need to be compromised if there are limited options for materials for a specific application.

3 PoF System in the Laboratory and Commercial Applications

The PoF system is one of the major focal points in the photonics industry and has been demonstrated in several applications including power transmission, IoT, 5G networks, and, quite recently, energy management system. Most of the PoF systems consists of the same three components, namely the LD, optical fiber and PV converter. The efficiency and output power of each application vary according to the specifications of the components used.

3.1 Experimental Setup and Applications

Figure 2 shows the summary of several applications that implement the usage of PoF technology. The PoF system in the laboratory and commercial applications are further discussed in terms of system efficiencies, types of LDs, optic fibers and PV converters, power loss, and limitations as well as improvements of the applications.

3.1.1 Communication

Optical fiber has long been known to bridge gaps in the communication sector. PoF was developed in 1978 by Deloach et al. to power up the sound alerter of the telephone. The experiment generates a 3-mW power supply from 830 nm light transmitted on an optical fiber. A year later, PoF concept was implemented by Miller and Lawry by using optically powered two-way speech communication over fiber and generating sound alarm at the remote station. Later in 1982, bidirectional speech-television communication over a single fiber was demonstrated. In addition, a highly efficient PV converter based on GaAlAs has been used to supply electrical power for the remote station telephone during power outages. In recent studies, PoF has been applied in various communication applications such as transmission of 5G NR signal, video monitoring system, integrating PoF in a 10 km long multicore fiber link within a 5G fronthaul scenario. In a study by de Souza et al., it was reported that the implementation of an optically powered 5G new radio (5G NR) fiber-wireless (FiWi) system consisted of a fiber coupled HPLD with a wavelength of 975 nm, a 100 m long MMF with 100/140 μm core, and PPC with a conversion efficiency of 30%. With these specifications, the overall power transmission efficiency (PTE) of 23.5% is experimentally demonstrated in a real 5G NR system.
According to Wang et al., a video monitoring system using PoF technique was introduced. The LD provided 1 W of optical power at 810 nm wavelength and MMF with a core diameter of 62.5 μm was used. The PPC generated up to 133 mW of power under a light illumination of 400 mW. However, the output power of the PPC was not high due to limitations of the core diameter of the used fiber. The implementation of PoF was also shown on the fronthaul of a 5G-NR network with an analog-radio-over-fiber on a 10-km long multicore fiber as demonstrated by López-Cardona et al. With an LD wavelength of 1480 nm, MMF was used alongside a PPC with a conversion efficiency of 30%. The power output recorded was the same as the previous study. Leaning onto these studies, it was found that the most prevalent issue involved the losses from each of the PoF components, with PV converters contributing to the highest amount of loss.

### 3.1.2 Environment

In the environmental sector, the PoF system has been implemented in the coal mining industry. Chen et al. illustrated an optically powered gas monitoring system to measure four essential environmental gases for underground mines. The PoF system was set up at 1550 nm using a SMF at a length of 250 m. The PPC used was of InGaAs material and it yielded a conversion efficiency of 30%. The highest power output recorded was 120 mW demonstrating longer distance coverage, reduced optical cabling, and increased multiplexing possibilities and data throughput for better awareness of underground environment using one fiber for both power delivery and communication. The study has allowed for future potential commercial implementation but will require improvements in terms of the software and hardware such as repetition of a more advanced UI/UX targeting integration into the end-user supervisory control and data acquisition (SCADA) system and a redesign of the gas monitoring station and accompanying remote terminal unit, respectively. With the rising issues of environmental hazards causing climate change, PoF systems should be pushed to be integrated with technological advancements, which can decrease the risks of environmental issues.

### 3.1.3 Energy management

In principle, energy management system ensures the usage of energy in an efficient manner and PoF has played a sizable role in this sector. In 1991, small-size power by light systems was demonstrated. The system consists of improved high-power LDs, large numerical aperture.
(NA) of fibers, GaAs cell, and DC–DC converter. The output power obtained is about 0.3 W over 1 m of 200 μm core fiber, and the full system efficiency is 5.5% from an evaluation of power by light systems. Miyakawa et al. discussed fiber optic power and signal transmission to apply powering information equipment. The conversion efficiency of PV cells remains constant with heat radiation and enhanced with limited series resistance. In 2006 and 2008, the ability of light to provide a new way of delivering power over nonconductive fiber was introduced. PoF was used for delivering power in optical networks by using optical fiber to power low-power switches and actuators while resistant to harsh environmental effects. PoF is also used to supply backup power to the battery in power failures.

PoF has also contributed to the energy management system where Li et al. showed that a novel multisensing functional system technique was developed. The PoF system consisted of 100 m MMF with 105 μm core diameter sourced by an 800 mW laser with 808-nm wavelength supplying power for remote module. The GaAs-clad PPC had a conversion efficiency of 40%. With the findings of this paper, the contradiction of high-power consumption and power supply can be balanced by an intelligent energy management system. Other than that, this paper further strengthens the notion of PoF being able to supply isolated power in harsh, noisy, and high-voltage environments. In Souza et al., PoF was used to supply remote sensors while transmitting and processing RF signals. In this work, a bidirectional radio-over-fiber (RoF) system with PoF capabilities was introduced where the illumination power of LD was 5W and its wavelength 1480 nm. The PPC conversion efficiency was found to be 25%, and an optical power of up to 1 W was converted to electrical power. In the recent reported work, a breakthrough of conversion efficiency improvement up to ~49% at 1466 nm has been demonstrated by Fafard and Masson, which could be further utilized for energy management system in the near future. It is important to note that although the PoF system is able to play a role in energy management system, there are still gaps within these studies that need to be addressed such as the overall system efficiency of PoF and high cost of PoF since high powered laser, PV power converters (PPC) and special optical fibers are used.

### 3.1.4 Internet of Things (IoT)

Moving forward, in a study related to PoF in 2019, PoF was used for smart node fed on IoT applications. The system used 300 m MMF and obtained full system efficiency of around 10%. In a recent study in 2020, PoF was used for smart power management by Helmers et al. The electrical power obtained is 5.5 W. Other than that, recent study reported an output power of 14 W for drones application at 808 nm wavelength. In addition, Fafard and Masson have also reported on PPC conversion at 17.5 W output with 60% of efficiency for the same wavelength, which could be beneficial for the IoT application. There is also a recent study in 2021 that shows an optimized PoF system can remotely feed a smart remote node for low-power applications. A custom PV laser power converter was developed and successfully tested to power up a smart remote node system that consumes 15.5 mW. The customized converter achieved a maximum conversion efficiency of 56.5% at 808 nm, which helped improve the overall system efficiency.

In the same year, research was done about using PoF in 5G network applications. A SMF cable was used to transmit 226 mW of electrical power to remote radio heads for communication, battery charge, and control. According to Park et al., the PoF system was used as the IoT sensor solution for the environmental monitoring of a set of submodules in MMC-HVDC systems. Laser modules of 1 W, 976 nm supplied focused light to an MMF with 62.5/125-μm core diameter, which was then converted at the PPC with a conversion power of 28% three PPCs with optical outputs up to 250 mW. Other than that, Mohammed et al. studied on the efficiency of the PoF system in distributing power for IoT applications and demonstrated the system in the short-haul distance as an alternative to copper cables. At 450 mA of laser driving current, the whole system efficiency reached a maximum of 12%. The data obtained clearly showed that system efficiency increases as laser driving current rises from 50 to 450 mA. The optical-to-electrical conversion module was chosen as the primary factor affecting the prototype’s overall system efficiency because it had a low power output. Although the PoF system allows for both power and data to be transmitted along the optic fiber, overall system efficiency is still not at its optimum.
3.1.5 Power system

In conventional power systems, copper cables are the more favorable line of transmission. However, new studies have shown that PoF systems are capable of supplying power via optic fiber. In 2010, PoF was used for temperature and current monitoring systems for transmission lines. Silica optical fiber cables are used in communications and power supply connections, resulting in the assurance of insulation between the sensor head and the consumer site. According to Hualong et al., high-power laser (HPL) over an SMF works for long-distance power supply in remote environments. 10 W fiber power is injected and transmitted through a 10 km SMF from a 1550-nm wavelength laser. In this study, the sensor receives 26 mW of converted power. The conversion occurs at the PPC where its chosen material is InGaAs. Guzowski et al., on the other hand, proposed the efficiency evaluation of ultralow power (ULP) supply. At 1310 nm laser source, fiber power is transmitted along a 0.5 m long SMF and converted at the PPC. The conversion efficiency was found to be 26.2% and the efficiency of whole system reached 13%. The PoF system in this study provided 350 μW of electric energy to power the ULP devices. Although the reviewed state-of-the-art PoF system seems to have a bright future, more studies must be conducted to transmit power over a long distance with minimum power loss and optimum overall system efficiency.

3.1.6 Sensors

PoF supply of microelectronic sensor devices is extremely useful in appliances working in harsh and remote environments. According to a paper presented by Zylka and Guzowski, a simple PoF system was constructed to deliver power required for remote supply of microprocessor-controlled low-power microelectronic sensing apparatus. A laser source of 10 mW with wavelength 654 nm was used in this experiment. The optical energy was transmitted along a multimode all-plastic fiber (APF) optical cable. In a study by Dimitriadou et al., an optically powered board designed for seabed monitoring operations was constructed. The power supply is clearly visible as the prominent peak at 1480 nm. Following optic-electric conversion a maximum of 190 mW is available on the sensor side. Other than improving and enhancing PoF efficiency and transmission distance, future PoF design can be done using the same optical fiber for both power and data transfer, performed simultaneously but at different wavelengths.

3.1.7 Others

PoF technology has also been implemented in various other applications. A combination of radio over fiber and remote optical powering over optical fiber was investigated by Wake et al. The system used a high-power LD with a maximum output of 2 W into 62.5 μm core diameter of MMF and 830 nm of wavelength. The optical power obtained from the laser is distributed over 300 m MMF, and the output power from PVC is regulated at 3.3 V. The system is designed for distributed antenna system application. According to Perhirin et al., an optical prototype dedicated to low-power submarine sensors that use PoF technology was demonstrated. The LD used has a central wavelength 1500 to 1600 nm and the power is transmitted along 10 km of optical fiber. The optoelectric conversion that occurs at the PPC contributes to the overall system efficiency of 22.5%. In 2014, PoF using 100 m of DCF for radio over fiber systems was introduced by Matsuura and Sato. The optical power obtained is up to 4.0 W, and the electrical power output to powering the base stations for wireless local area network (WLAN) is more than 400 mW. In 2015, Sato et al. demonstrated PoF using DCF optically powered ROF systems with 40 W of optical feeding obtained. In the same year, Matsuura et al. presented 60 W optical power obtained over a 300 m DCF with improved system efficiency. In 2017, PoF was used for a fishing camera over MMF as the fishing line. The electrical power output obtained is 413 mW with 1.27 W of optical power required from high-power LDs. In 2018, Kamiyama et al. used PoF for multichannel data signals and power distribution using a DCF. The maximum optical power feed is 60 W, and the optical power delivered to a remote unit is then converted into electrical power by several PPC.
Table 3 shows a summary of the different PoF experiments conducted and their respective applications from 2008 to 2022. Most of the experiments that are listed in the table involved sending power and data simultaneously to low-power sensors and communication devices such as remote antenna units (RAU) and remote radio heads (RRH). The overall system efficiency stated in the experiments listed ranges from 9% to as high as 28.6%, which was achieved by Matsuura et al.\textsuperscript{3}. The experiment used an erbium-doped fiber amplifier (EDFA) and bandpass filters to increase the output power and reduce noise, respectively. The tapered fiber bundle combiner (TFBC) used in the research was also fabricated by tapering and fusing the bundles of fiber with the DCF they used to reduce connection loss. Apart from the overall system efficiency, it is also observed that the most frequently used wavelength operation is 808 nm due to its compatibility with most PV cells and power converter also its availability in the commercial market. Moreover, that 808 nm frequency can improve system energy efficiency for silica fibers and applications with a link length of \(<1.3\) km.\textsuperscript{13}

3.2 Commercialized PoF Systems

There are a range of commercial systems that can be observed at in-depth. There are several available commercialized PoF systems from companies that are able to deliver power to remote and inaccessible areas. One of the PoF systems that have been commercialized operates at 830 nm wavelength, which provides electrical distribution to remote locations.\textsuperscript{96} One of their novelties is that they have supercapacitors to ensure a smooth and constant voltage is supplied to the remotely powered devices. Since the PoF system uses MMF with a large core size, the electrical output power declines over a certain distance because of the modal dispersion inside the cable.\textsuperscript{49} Therefore, the PoF system is more suitable for short-distance applications. Another commercialized PoF system used a wavelength of 976 nm for smart monitoring system for electrical assets such as switchgears and busbars. The optical power of the transmitted light is converted into electrical power using the sensor modules.\textsuperscript{97} It provides power for sensors that continuously monitor temperature, humidity, and partial discharge. Other than that, at the wavelength of 750 to 850 nm and 900 to 1000 nm, a different PoF system allows different power inputs with a maximum power output of 1 W to be compatible with various laser sources. Fiber optic cable with core sizes of 62.5/100 \(\mu\)m is used to transmit power.\textsuperscript{98} The designed system provides electrical sources in remote, inaccessible, hazardous, electrically noisy, or exposed to extreme weather locations. The typical application of the system is to power up low wattage electronic devices such as sensors, actuators, data communication transceivers, GPS receivers, and gauges, with the limitation of 1 W output power. Overall, each commercialized PoF system has been designed to produce the necessary output power and voltage for their respective applications. However, all of them have their own set of limitations. The optimization of these systems can be explored more thoroughly by using numerical methods or techniques involving artificial intelligence, such as a genetic algorithm.

3.3 Patented PoF Systems

Table 4 lists the commercial patents of PoF that focuses on the various methods of transmitting power and data simultaneously to sensors and communication devices. These patents initially started from designing the optical network that can transmit power and data. Since then, more patents have been created that contain methods for providing digital data services and power in an optical fiber-based distributed communication system. The keywords, power over fiber, was used for patent search on Espacenet\textsuperscript{118} and Patentscope.\textsuperscript{119} The keywords were entered into all fields/any field section of the databases in September 2022. The patents in Table 4 discuss industrial applications of PoF systems, such as controlling remote antenna units and acoustic sensing for a barrier.

There are two patents in 2010 that highlighted the methods of transmitting power through optical fiber. The first patent focused more on the method of transmitting power and data simultaneously to network equipment such as wireless access points using an optical network. The method uses the electrical signal that includes low- and high-frequency data signal to transmit power and data. A filter is used to separate the data and power signal before the data signal is transmitted.
**Table 3** A summary of the different PoF applications available and its values of power, types of fiber, efficiency, PV material, and loss.

<table>
<thead>
<tr>
<th>Ref No.</th>
<th>Data</th>
<th>Power input</th>
<th>Laser driver (power)</th>
<th>Laser cooling (power)</th>
<th>Laser</th>
<th>Laser conversion + fiber (power)</th>
<th>Types of fiber</th>
<th>Length</th>
<th>Power output</th>
<th>PV conversion (power)</th>
<th>DC/DC power</th>
<th>PV conversion efficiency (%)</th>
<th>PV material</th>
<th>Power loss (db)</th>
<th>Overall system efficiency (%)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>Yes</td>
<td>NA</td>
<td>20 mW</td>
<td>NA</td>
<td>405 nm 650 nm</td>
<td>20 mW (injected to fiber) 4.12 mW (fiber end)</td>
<td>SI-POF</td>
<td>10 m</td>
<td>Pelec: 6.36 mW</td>
<td>10 mW</td>
<td>NA</td>
<td>38%</td>
<td>GaAs</td>
<td>1.5 dB</td>
<td>~9%</td>
<td>In-home use and IoT systems</td>
</tr>
<tr>
<td>87</td>
<td>Yes</td>
<td>10 mW</td>
<td>NA</td>
<td>NA</td>
<td>654 nm</td>
<td>NA</td>
<td>APF</td>
<td>10 m</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>GaAs</td>
<td>NA</td>
<td>NA</td>
<td>Simplifying microelectronic sensor devices</td>
</tr>
<tr>
<td>11</td>
<td>No</td>
<td>NA</td>
<td>250 mW</td>
<td>NA</td>
<td>780–980 nm</td>
<td>NA</td>
<td>SMF</td>
<td>NA</td>
<td>0.5 W</td>
<td>1 W</td>
<td>NA</td>
<td>41%</td>
<td>GaAs</td>
<td>NA</td>
<td>NA</td>
<td>Using optical fiber to measure current in high-voltage applications (network monitoring)</td>
</tr>
<tr>
<td>10</td>
<td>Yes</td>
<td>NA</td>
<td>3 W</td>
<td>NA</td>
<td>808 nm</td>
<td>NA</td>
<td>DCF</td>
<td>NA</td>
<td>20 V</td>
<td>600 mW (rated)</td>
<td>5 V</td>
<td>NA</td>
<td>GaAs</td>
<td>NA</td>
<td>NA</td>
<td>High voltage systems</td>
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<tr>
<td>25</td>
<td>Yes</td>
<td>17 V</td>
<td>12 V</td>
<td>NA</td>
<td>808 nm</td>
<td>400 mW</td>
<td>MMF</td>
<td>55 m</td>
<td>375 mW</td>
<td>276 mW</td>
<td>NA</td>
<td>NA</td>
<td>GaAs</td>
<td>1.58 dB</td>
<td>NA</td>
<td>Bidirectional communication with sensors</td>
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<tr>
<td>48</td>
<td>Yes</td>
<td>NA</td>
<td>150 W</td>
<td>NA</td>
<td>808 nm</td>
<td>NA</td>
<td>DCF</td>
<td>300 m</td>
<td>43.7 W</td>
<td>NA</td>
<td>NA</td>
<td>40%</td>
<td>GaAs</td>
<td>12%</td>
<td>NA</td>
<td>Remote antenna units for telecommunication applications</td>
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<tr>
<td>90</td>
<td>No</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>808 nm</td>
<td>1.5 W</td>
<td>MMF 200 um</td>
<td>200 m</td>
<td>0.2 W</td>
<td>228 mW</td>
<td>3.3V</td>
<td>22.8%</td>
<td>GaAs</td>
<td>0.01 W</td>
<td>NA</td>
<td>Active infrared imaging systems</td>
</tr>
</tbody>
</table>

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### Table 3 (Continued)

<table>
<thead>
<tr>
<th>Ref No.</th>
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<th>Laser driver (power)</th>
<th>Laser cooling (power)</th>
<th>Laser</th>
<th>Laser conversion + fiber (power)</th>
<th>Types of fiber</th>
<th>Length</th>
<th>Power output</th>
<th>PV conversion (power)</th>
<th>DC/DC power</th>
<th>PV conversion efficiency (%)</th>
<th>PV material</th>
<th>Power loss (%)</th>
<th>Overall system efficiency (%)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>Yes</td>
<td>18 V</td>
<td>(70 W = 2 laser)</td>
<td>60 W</td>
<td>808 nm</td>
<td>60 W and 70 W</td>
<td>DCF</td>
<td>300 m</td>
<td>“10 W: 2.36 W/18.5 V”</td>
<td>10-W (6 PPC)</td>
<td>NA</td>
<td>24%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Send data signals and transmit power to multiple channels</td>
</tr>
<tr>
<td>91</td>
<td>Yes</td>
<td>NA</td>
<td>60 W</td>
<td>60 W</td>
<td>808 nm</td>
<td>NA</td>
<td>DCF</td>
<td>300 m</td>
<td>NA</td>
<td>26.7 W</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Radio-over-fiber networks</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>12 V</td>
<td>1.27 W</td>
<td>NA</td>
<td>808 nm</td>
<td>1.27 W</td>
<td>MMF</td>
<td>30 m</td>
<td>413 mW</td>
<td>NA</td>
<td>NA</td>
<td>32.6%</td>
<td>GaAs</td>
<td>NA</td>
<td>NA</td>
<td>Fishing camera system</td>
</tr>
<tr>
<td>39</td>
<td>Yes</td>
<td>NA</td>
<td>(40 W = two laser)</td>
<td>(20 W = one laser)</td>
<td>808 nm</td>
<td>40 W</td>
<td>DCF</td>
<td>300 m</td>
<td>7.5 W</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>7.29 dB</td>
<td>NA</td>
<td>Supplying optical power to radio-over-fiber systems</td>
</tr>
<tr>
<td>89</td>
<td>Yes</td>
<td>NA</td>
<td>60 W</td>
<td>60 W</td>
<td>808 nm</td>
<td>60 W</td>
<td>DCF</td>
<td>300 m</td>
<td>26 W</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Supplying optical power to remote antenna units in radio-over-fiber systems</td>
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<tr>
<td>92</td>
<td>No</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>808 nm</td>
<td>NA</td>
<td>MMF</td>
<td>NA</td>
<td>31.14 mW</td>
<td>NA</td>
<td>NA</td>
<td>51.9%</td>
<td>GaAs</td>
<td>NA</td>
<td>NA</td>
<td>Transfer of optical power</td>
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<tr>
<td>69</td>
<td>Yes</td>
<td>800 mW</td>
<td>NA</td>
<td>NA</td>
<td>808 nm</td>
<td>NA</td>
<td>MMF</td>
<td>100 m</td>
<td>238 mW</td>
<td>NA</td>
<td>225 mV</td>
<td>40%</td>
<td>GaAs</td>
<td>NA</td>
<td>NA</td>
<td>Using PoF transmission in a novel remote multisensing energy management system</td>
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</table>
Table 3 (Continued).

<table>
<thead>
<tr>
<th>Ref No. Data</th>
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<th>Laser</th>
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<th>Types of fiber</th>
<th>Length</th>
<th>Power output</th>
<th>PV conversion (power)</th>
<th>DC/DC power</th>
<th>PV conversion efficiency (%)</th>
<th>PV material</th>
<th>Power loss</th>
<th>Overall system efficiency (%)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>82 Yes 12 V</td>
<td>9.8 W</td>
<td>10.2 W</td>
<td>809 nm</td>
<td>15.2 W</td>
<td>MMF: Core diameter (400 μm)</td>
<td></td>
<td>1.5 m</td>
<td>5.5 W</td>
<td>6.9 W</td>
<td>1.6 W</td>
<td>51-54%</td>
<td>GaAs</td>
<td>15.2 W</td>
<td>~11%</td>
<td>Smart power management</td>
</tr>
<tr>
<td>16 Yes 12 V/ ~50 W</td>
<td>29.22 W</td>
<td>15 W</td>
<td>809 nm</td>
<td>NA</td>
<td>MMF</td>
<td></td>
<td>5 W</td>
<td>3.3 V</td>
<td>7.13 W</td>
<td>NA</td>
<td>&gt;51%</td>
<td>GaAs</td>
<td>NA</td>
<td>11.1%</td>
<td>Power supply using power-by-light systems</td>
</tr>
<tr>
<td>13 Yes NA</td>
<td>NA</td>
<td>15 W/ 809 nm</td>
<td>1.69 W</td>
<td>1 m</td>
<td>MMF: GI-silica (62.5/12 μm)</td>
<td></td>
<td>240 mW</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>52% 34%</td>
<td>GaAs</td>
<td>InGaAs</td>
<td>NA</td>
<td>Using fiber optics to provide optical power remotely</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2) 200 μm: 8.79 W</td>
<td>1 m</td>
<td>SI-silica (200/50 μm)</td>
<td></td>
<td>409 mW</td>
<td>SI-silica</td>
<td>360 mW</td>
<td>NA</td>
<td>26%</td>
<td>InP</td>
<td>NA</td>
<td>NA</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>300 m</td>
<td>SI-POF (980/1000 μm)</td>
<td></td>
<td>197 mW</td>
<td>SI-POF</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td></td>
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<tr>
<td>79 Yes 1 W</td>
<td>NA</td>
<td>NA</td>
<td>810 nm</td>
<td>3 W</td>
<td>MMF (62.5 μm core diameter)</td>
<td></td>
<td>NA</td>
<td>133 mW</td>
<td>400 mW</td>
<td>NA</td>
<td>44.5%</td>
<td>GaAs</td>
<td>NA</td>
<td>~39%</td>
<td>Using PoF technique in video monitoring system</td>
</tr>
<tr>
<td>38 Yes NA</td>
<td>4 W</td>
<td>NA</td>
<td>830 nm</td>
<td>3.6 W</td>
<td>DCF</td>
<td></td>
<td>100 m</td>
<td>585.14 mW</td>
<td>NA</td>
<td>NA</td>
<td>28.6%</td>
<td>NA</td>
<td>4.47 dB</td>
<td>NA</td>
<td>Radio over fiber systems</td>
</tr>
<tr>
<td>22 Yes NA</td>
<td>NA</td>
<td>NA</td>
<td>SMF: 830 nm MMF: 1480 nm</td>
<td>2.2 km</td>
<td>NA</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>SMF: InGaAs MMF: GaAs</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Telecommunications and electric utilities in the development of smart grid</td>
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<tr>
<td>Ref No.</td>
<td>Data</td>
<td>Transmitter</td>
<td>Fiber</td>
<td>Receiver</td>
<td>Overall system efficiency (%)</td>
<td>Application</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>5</td>
<td>Yes</td>
<td>NA</td>
<td>MMF 40 m</td>
<td>NA</td>
<td>3.5 V</td>
<td>0.43 dB</td>
<td>NA</td>
<td>NA</td>
<td>0.43 dB</td>
<td>NA</td>
<td>Current and temperature monitoring system</td>
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<td></td>
<td></td>
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<td>2</td>
<td>Yes</td>
<td>29% E-O conversion</td>
<td>NA 830 nm</td>
<td>MMF-Silica 300 m</td>
<td>92.55 mW</td>
<td>9.83%</td>
<td>AlGaAs 3.5 dB</td>
<td>NA</td>
<td>23.5%</td>
<td>Using optical power for transmission of 5G NR signal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>Yes</td>
<td>30 W</td>
<td>NA 840 nm</td>
<td>MMF 100 m</td>
<td>475 mW</td>
<td>7 V</td>
<td>37%</td>
<td>GaAs</td>
<td>340 mW NA</td>
<td>37%</td>
<td>Using optical power for transmission of 5G NR signal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Yes</td>
<td>10 W</td>
<td>NA 975 nm</td>
<td>MMF (100 μm diameter) 100 m</td>
<td>1.4 W</td>
<td>NA</td>
<td>30%</td>
<td>SI</td>
<td>100 m</td>
<td>30%</td>
<td>Using optical power for transmission of 5G NR signal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>Yes</td>
<td>50 mW</td>
<td>NA 976 nm</td>
<td>MMF (625 μm core diameter) 6 m</td>
<td>0.75 W</td>
<td>NA</td>
<td>28%</td>
<td>SI</td>
<td>250 mW NA</td>
<td>28%</td>
<td>Using optical power for transmission of 5G NR signal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>No</td>
<td>NA</td>
<td>SMF 0.5 m</td>
<td>NA</td>
<td>0.7 mW</td>
<td>NA</td>
<td>0.35-0.41 V</td>
<td>NA</td>
<td>26.2%</td>
<td>Using POE to evaluate low power supply systems</td>
<td></td>
<td></td>
<td></td>
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</table>

Table 3 (Continued)
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<tr>
<th>Ref No.</th>
<th>Data</th>
<th>Transmitter</th>
<th>Fiber</th>
<th>Receiver</th>
<th>Overall system efficiency (%)</th>
<th>Application</th>
</tr>
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<tbody>
<tr>
<td>93</td>
<td>Yes</td>
<td>NA</td>
<td>SMF</td>
<td>NA</td>
<td>93 Yes NA NA NA 1455 nm 10.7–33.1 mW SMF: 25 km DSF: 10 km 2.14–6.6 mW NA NA 20% InP NA NA</td>
<td>Optical powering of wavelength division multiplexing (WDM) communication system</td>
</tr>
<tr>
<td>94</td>
<td>No</td>
<td>NA</td>
<td>MCF/MMF</td>
<td>20 km</td>
<td>Individual MCF: four cores: 194.52 mW Seven cores: 389.04 mW Sharing MCF: four cores: 618.04 mW NA NA NA NA NA NA</td>
<td>5G networks</td>
</tr>
<tr>
<td>50</td>
<td>Yes</td>
<td>800 mW</td>
<td>MMF</td>
<td>NA</td>
<td>50 Yes 800 mW NA NA 1480 nm NA NA 133 mW 200 mW NA 30% NA NA NA</td>
<td>Integrating PoF in a 10 km long multicore fiber link within a 5G fronthaul scenario</td>
</tr>
<tr>
<td>81</td>
<td>Yes</td>
<td>5 W</td>
<td>SMF</td>
<td>NA</td>
<td>81 Yes 5 W NA NA 1480 nm 3.2 W SMF NA 360 mW NA NA 25% NA 30 dB NA</td>
<td>Supply remote sensors while transmitting and processing RF signals</td>
</tr>
<tr>
<td>Ref No.</td>
<td>Data</td>
<td>Power input</td>
<td>Laser driver (power)</td>
<td>Laser cooling (power)</td>
<td>Laser conversion + fiber (power)</td>
<td>Types of fiber</td>
</tr>
<tr>
<td>---------</td>
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</tr>
<tr>
<td>95</td>
<td>Yes</td>
<td>NA</td>
<td>5 × 2.2 W</td>
<td>NA</td>
<td>MCF/MMF</td>
<td>1 km</td>
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<tr>
<td>6</td>
<td>No</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>10 km</td>
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<tr>
<td>3</td>
<td>Yes</td>
<td>NA</td>
<td>2–4 W</td>
<td>NA</td>
<td>NA</td>
<td>1550 nm</td>
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<tr>
<td>80</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>1550 nm</td>
</tr>
<tr>
<td>86</td>
<td>No</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>1550 nm</td>
</tr>
<tr>
<td>68</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>MMF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200 m</td>
</tr>
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</table>

* PV conversion efficiency = DCF/4 W
<table>
<thead>
<tr>
<th>Ref no.</th>
<th>Patent application no.</th>
<th>Applicant; publication date; country</th>
<th>Status in September 2022 (family members)</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>US7359647B1</td>
<td>NORTEL NETWORKS LTD; April 15, 2008, USA</td>
<td>NONE</td>
<td>An apparatus for receiving power and data signals using an optical signal within a predetermined wavelength range</td>
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<tr>
<td>100</td>
<td>US7813646B2</td>
<td>RLH IND INC; October 12, 2010; USA</td>
<td>US2009016715A1</td>
<td>A PoF system is capable of generating up to 30 mA (milliamps) of electricity at 24 volts for use with remotely deployed electrical equipment</td>
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<td>101</td>
<td>US8270838B2</td>
<td>COX TERRY D; CORNING CABLE SYS LLC; September 18, 2010; USA</td>
<td>AU2010101508A4; AU2010247971A1; CN102428663A; CN102428663B; EP2430778A1; US2010290787A1; US2012163829A1; US8155525B2; WO2010132292A1</td>
<td>An interconnect unit for a distributed wireless communication system, comprising: a plurality of communication links each configured to carry electrical RF signals from a head-end unit to a plurality of remote units</td>
</tr>
<tr>
<td>102</td>
<td>US8155525B2</td>
<td>COX TERRY D [US]; CORNING CABLE SYS LLC; April 12, 2012; USA</td>
<td>AU2010101508A4; AU2010247971A1; CN102428663A; CN102428663B; EP2430778A1; US2010290787A1; US2012163829A1; US8270838B2; WO2010132292A1</td>
<td>A power distribution module electrically coupled between the one power supply and the plurality of power branches and configured to distribute power to the plurality of remote units</td>
</tr>
<tr>
<td>103</td>
<td>WO2016070946</td>
<td>PRYSMIAN S.P.A; May 12, 2016; USA</td>
<td>BR112017009284A2; CN107533194A; CN107533194B; DK215876T3; EP3215876A1; EP3215876B1; ES2909898T3; US10197725B2; US2018335563A1</td>
<td>A multimode optical fiber for continuous transmission of electromagnetic radiation at high power</td>
</tr>
<tr>
<td>Ref no.</td>
<td>Patent application no.</td>
<td>Applicant; publication date; country</td>
<td>Status in September 2022 (family members)</td>
<td>Summary</td>
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<td>104</td>
<td>US20170039826A1</td>
<td>OPTASENSE HOLDINGS LTD; February 9, 2017; USA</td>
<td>WO2015159081A1</td>
<td>A system for monitoring a perimeter having a barrier comprising of a sensing optical fiber wherein the sensing fiber is mechanically coupled to at least one vibration transmitting element which is mechanically coupled to the barrier</td>
</tr>
<tr>
<td>105</td>
<td>US9853732B2</td>
<td>CORNING OPTICAL COMMUNICATIONS LLC; December 26, 2017; USA</td>
<td>US2011268452A1; US2017099107A1; US9525488B2</td>
<td>A method for providing digital data services and/or power in an optical fiber based distributed communications system</td>
</tr>
<tr>
<td>106</td>
<td>US9979491B2</td>
<td>TELEDYNE INSTRUMENTS INC; March 22, 2018; USA</td>
<td>US2018083715A1</td>
<td>A subsea PoF control area network (&quot;CAN&quot;) bus converter system</td>
</tr>
<tr>
<td>107</td>
<td>US20180198400</td>
<td>TURNER QIAN; TABORISSKIY YURIY; July 12, 2018; USA</td>
<td>US10363834B2</td>
<td>A power over fiber that receives module at the low voltage section of a vehicle having an electric traction motor</td>
</tr>
<tr>
<td>108</td>
<td>CN108398147</td>
<td>MH GOPOWER COMPANY LTD; August 14, 2018; China</td>
<td>TW201829984A; US10608830B2; US201827133A1</td>
<td>A power over fiber technology that is able to provide power and communication to one or more and multiple sensors through an optical fiber. The invention claims a sensing system capable of generating power by using a PPC and one sensor</td>
</tr>
<tr>
<td>108</td>
<td>US10608830B2</td>
<td>MH GOPOWER COMPANY LTD; March 31, 2020; USA</td>
<td>CN106398147A; TW201829984A; US2018227133A1</td>
<td>PoF system that is able to detect lower intensity PD events than traditional acoustic, or UHF PD sensors mounted on compartment walls instead of directly on high voltage areas like bus bars</td>
</tr>
<tr>
<td>Ref no.</td>
<td>Patent application no.</td>
<td>Applicant; publication date; country</td>
<td>Status in September 2022 (family members)</td>
<td>Summary</td>
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<tr>
<td>110</td>
<td>US10750442B2</td>
<td>CORNING OPTICAL COMMUNICATIONS LLC; August 18, 2020</td>
<td>US10104610B2; US10420025B2; US2014308043A1; US2015382293A1; US2017203018A1; US2019037492A1; US201936498A1; US9160449B2; US9669723B2</td>
<td>A method of managing the power consumed at an RAU in a distributed antenna system; the method comprises determining an available power budget for at least one powered port configured to provide power to at least one external power-consuming device connected to the at least one powered port based on power required by at least one power-consuming RAU module</td>
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</table>
| 111    | US10911157B1           | KYOCERA CORP; February 2, 2021; USA | CN112311473A; EP3772194A1; JP2021027656A; US1123428B2; US2021036784A1; US2021111813A1 | • A first data communication device including a power sourcing equipment device including a semiconductor laser that oscillates with electric power, thereby outputting feed light  
• A second data communication device including a powered device including a photoelectric conversion element that converts the feed light into electric power, the second data communication device performing optical communication with the first data communication device  
• An optical fiber cable including a first end connectable to the first data communication device and a second end connectable to the second data communication device to transmit the feed light and signal light |
<p>| 112    | US20210247578          | KYOCERA CORP; August 12, 2021, USA | CN112558591A; CN11255891B; EP3829085A1; EP3829085A4; JP2021002715A; JP6814293B2; US11137561B2; WO2020255636A1 | A power over fiber system that transmits feed light and signal light through an optical fiber including a first transmission path being a core or a cladding; and a second transmission path being a cladding located on a periphery of the first transmission path |
| 113    | WO2021186831A1         | KYOCERA CORP; September 23, 2021, USA | JP2021150659A; JP7084441B2; | An optical transmitter that transmits signal light modulated by an electric signal and feed light for supplying power, a core transmits the signal light, and a core formed around the core |</p>
<table>
<thead>
<tr>
<th>Ref no.</th>
<th>Patent application no.</th>
<th>Applicant; publication date; country</th>
<th>Status in September 2022 (family members)</th>
<th>Summary</th>
</tr>
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<tbody>
<tr>
<td>114</td>
<td>US2021409116A1</td>
<td>ROHDE &amp; SCHWARZ; December 30, 2021; USA</td>
<td>NONE</td>
<td>A PoF system, comprising: a measurement device, wherein the PoF system powers a measurement probe of the measurement device, with the system being electrically isolated from the measurement probe, and the PoF system</td>
</tr>
<tr>
<td>115</td>
<td>US2022094449A1</td>
<td>KYOCERA CORP; March 24, 2022; USA</td>
<td>CN113544928A; EP3930216A1; JP2020202423A; JP6890631B2; WO2020246375A1</td>
<td>An optical connector of a power over fiber system, comprising a shutter that opens in conjunction with a connection operation to enable the connection and closes in conjunction with a disconnection operation to block feed light from exiting</td>
</tr>
<tr>
<td>116</td>
<td>US2022236490A1</td>
<td>MACLEON LLC; July 28, 2022; USA</td>
<td>US2022234937A1; US2022234938A1; US2022236509A1; WO2022159782A1</td>
<td>An overall power over fiber system capable of efficiently transporting ultra-high power across great distances with significantly low loss</td>
</tr>
<tr>
<td>117</td>
<td>EP4047838A1</td>
<td>KYOCERA CORP; August 24, 2022; France</td>
<td>CN114556735A; JP2021068937A; JP2021193839A; JP6892089B2; JP7117435B2; WO2021075087A1</td>
<td>A PoF system that includes a temperature sensor that detects a temperature in the power sourcing equipment, and a controller that performs a process of switching electric power input to the semiconductor laser, based on the temperature detected by the temperature sensor</td>
</tr>
</tbody>
</table>
processed. The inventor of the patent highlighted that the conversion efficiency and the amount of current produced depend on the equipment’s power rating that needs to be powered so that the method can have different performance based on the applications. The second patent also proposed a method of distributing power through an optical fiber that includes a receiver unit sending a feedback signal to the transmit unit to control and regulate laser sources. The patent improved the safety of the PoF system by first operating the transmit unit at low power levels until a feedback signal indicates that all safety and operational checks have been performed.

As the use of the PoF system increases in industrial applications, two patents were published later in 2012 that proposed providing power in radio frequency applications using converter pairs connected using optical fibers. The converter pair comprises of electrical-to-optical converters that include lasers and optical-to-electrical converters that include photodiodes. The same inventor published both patents, and the inventions helped provide alternatives to creating more picocells that can increase radio frequency network coverage. The widespread use of PoF systems became apparent in 2017 when two patents about providing digital data services in optical-fiber-based communication systems were published. The two patents proposed a more efficient method of supplying power to data service clients instead of providing a standalone power source for each data client.

There are also three patents in 2017 and 2020 that have made contributions to PoF system’s innovation. The patent in 2017 is about designing a perimeter monitoring system using fiber-optic distributed acoustic sensing. The system used PoF because any acoustic disturbance will trigger an interrogator module consisting of a laser and photodetector to produce a series of optical pulses. One of the design advantages is that the burying of sensing fiber isolates them from environmental effects and produce better signal-to-noise ratio. The first patent in 2020 is an invention of a sensor system that can be enabled by PoF. One of the claims of the invention is that it can power up multiple sensors using one laser source. However, the patent inventor stated that the PPC within the sensor module might not provide enough continuous power to operate all sensors continuously. The patent of the invention that can solve the problem was published in the same year that proposed a power management system of remote units. Inventions that were patented in 2021 were found to revolve around communication and measurement devices while patents reported in 2022 were on the inventions of temperature sensors and an optical connector of power over fiber system. A patent published on the 28th of July 2022 claims that their overall power over fiber system capable of efficiently transporting ultrahigh power across great distances with significantly low loss was due to the unreliability of conventional power over fiber systems using silica-based fiber, which constrained transmission and distribution losses, conversion efficiencies at both the transmit and receive ends, and significant attenuation in the transport medium.116 The PoF patents published over the decade have shown how far PoF has progressed in research and the potential of PoF systems in the future.

4 Challenges and Recommendations

The market penetration of the PoF system remains inconclusive due to the great challenges encountered throughout its technological development. In this section, the issues, and challenges in the PoF system are extensively discussed, together with the recommendations to overcome the challenges.

4.1 System Efficiency

Several potential ways to increase the efficiency of the overall PoF system involve increasing the efficiency of the transmitter, optical fiber, and receiver. It has been discussed in previous work120 that variables such as absorption efficiency, quantum efficiency, storage efficiency, and extraction efficiency depend directly on the choice of laser material. The work concluded that Neodymium (Nd) type lasers were widely used for most applications such as laser delivery and high energy storage. One of the challenges that must be tackled by researchers is to choose what type of laser materials can give the best results for their projects where the performance requirements are different. It is recommended for researchers to consider the four variables mentioned when selecting a laser material for their transmitter.
For the optical fiber, one of the main aspects of selecting the suitable optical fiber cable is the amount of attenuation or loss of the transmitted power. There are low-cost options available such as plastic optical fiber, but one must consider their higher attenuation than conventional glass optical fiber cables. The attenuation loss can happen due to Rayleigh scattering, absorption of light by the optical fiber cable, geometrical interferences at cladding core interface, and attenuation within the optical cladding. In a study by Matsui et al., it has been mentioned that SMF and MMF optic fiber cables have a fixed value of attenuation in dB/km for a given wavelength, which makes them most frequently used for PoF applications. Another important aspect in selecting the suitable optical fiber cable is their capacity on how much power they can withstand. For example, SMF might be unreliable in projects that require high power transmission due to limited power density of the small core effective area. Therefore, fiber cables that can withstand higher power, such as DCF and MMF, might be more compatible. After selecting an optical fiber cable based on these two important aspects, there are other challenges in working with optical fiber cables for PoF system, such as splicing losses and mismatching effects. Using the same type of cable with the same core size throughout the PoF system can increase the efficiency of the transmission medium.

The receiver in the PoF system is a power conversion module that converts optical power from optic fiber cable back to electrical power that can be transmitted to the load. The module consists of PPC devices that are made up of semiconductor materials. The most common semiconductor materials used are Si, GaA, InGaAs, and GaSb. The main differences between these materials can be found in an open-circuit voltage for a single-cell converter and their energy gap. The type of semiconductor materials needs to be selected by considering five aspects, which are the amount of dark current, sensitivity, wavelength, quantum efficiency, and conversion efficiency. The selection of the type of materials that needs to be used can also be different depending on the cost and performance requirement of the projects.

4.2 Others

PoF systems have also shown some limitations in terms of only being able to supply continuous power to multiple devices from a single laser source. However, there have been inventions from the published patents that can solve the problem by using power management systems. In high-power laser application, there may also be a laser safety issue associated with several watts of optical power, leaving the fiber when it is broken. However, systems are already available that include engineering controls as a control measure to avoid the potential hazards. With more developing research and technology toward the PoF system, the cost of optical components can be reduced. There will be higher potential in terms of available power and conversion efficiency. Eventually, PoF technology can be implemented as a backup supply as an alternative to electrical conductors.

5 Conclusion

PoF systems have shown their potential in research and industrial sectors throughout the decade. Research of PoF systems started with the implementation of PoF in temperature and current monitoring systems. It later expanded to the power distribution system of remote antenna units and radio over fiber systems. Recently, research is concentrated on the ability of the PoF system to facilitate simultaneous power and data transmission that can be essential in future communication devices. The commercial and patented PoF systems presented in this review also show that PoF systems have become essential in industrial applications. They are being used in digital data services and picocells production that makes up the coverage of radio frequency networks. However, more study needs to be done on optimizing the energy conversion in the PoF system to ensure the cost-effectiveness and commercial viability of PoF. This review discussed the components of PoF, commercial and patented PoF systems where their performance, development, and suitable applications were elaborated. The problems of the study were highlighted and concluded with the recommendations for future research. The overall review will hopefully serve as an extension to the current work of the PoF system and guideline to the future development of PoF.
Acknowledgments

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References

83. N. Shindo et al., “Optically powered and controlled drones using optical fibers for airborne base stations” (2022).

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Farah Aniza Mohd Yusof received her MS degree in electronic engineering from the Universiti Putra Malaysia in 2008. She is a senior engineer at TNB. She has more than 15 years of experience in SCADA. Her interest is in master system and SCADA protocol.