photonics

Article

Demonstration of an In-Flight Entertainment System Using Power-over-Fiber

Joao B. Rosolem [1,*], Fabio R. Bassan [1], Marcelo P. de Oliveira [2], Alexandre B. dos Santos [2] and Leonardo M. Wollinger [2]

[1] CPQD—Research and Development Center in Telecommunications, Campinas 13086-902, SP, Brazil; fbassan@cpqd.com.br
[2] Embraer, São José dos Campos 12227-901, SP, Brazil; oliveira.marcelo@embraer.com.br (M.P.d.O.); albsanto@embraer.com.br (A.B.d.S.); leonardo.wollinger@embraer.com.br (L.M.W.)
* Correspondence: rosolem@cpqd.com.br

Abstract: The use of optical fibers is increasing in modern aircraft because this helps solve challenges of size, weight, communication, and reliability in new generation aircraft. This study describes a video and power transmission system using optical fibers (PoF) for in-flight entertainment (IFE) system application. We present the benefits and the limitations of this application, and we perform two practical experiments to demonstrate their performance. We used off-the-shelf devices in the experiments, such as one 15-Watt semiconductor laser operating at 808 nm, GaAs photovoltaic converters, optical transmitters and receivers, and video monitors. The power and video signals were transmitted using two 50-m length multimode fibers. In addition, we proposed and tested two types of energy transformation units (ETUs), which are responsible for supplying electrical energy to the IFE video monitor and the optical fiber receiver.

Keywords: power-over-fiber; PoF; in-flight entertainment; IFE; avionics; optical fibers; high optical power

Citation: Rosolem, J.B.; Bassan, F.R.; de Oliveira, M.P.; dos Santos, A.B.; Wollinger, L.M. Demonstration of an In-Flight Entertainment System Using Power-over-Fiber. *Photonics* **2024**, *11*, 627. https://doi.org/10.3390/photonics11070627

Received: 16 May 2024
Revised: 6 June 2024
Accepted: 27 June 2024
Published: 1 July 2024

1. Introduction

Size, weight, power consumption, and cost (SWaP-C) are very important factors for aviation, as they affect aircraft efficiency [1]. Aircraft designers are always looking to reduce size, weight, and power consumption to create better fuel efficiency and reduce operating costs.

In this context, the use of optical fibers in aircraft helps to solve some SWaP-C challenges related to size and weight. In absolute terms, the copper density of the wires is 8.7 g/cm^3 versus 2.4 g/cm^3 for glass [2]. This means that disregarding the protective elements, copper wire cables weigh 3.6 times more than fiber optic cables. Although it is difficult to provide an exact weight for fiber optic and copper cables, as they can vary greatly depending on the specific cable design and manufacturer, some numbers can be accessed from the literature. According to [3], the in-flight entertainment (IFE) systems installed in current cabins use a minimum of 1 km of Ethernet cable with a weight of 41 kg/km. On the other hand, optical fiber cables present a weight of 4.2 kg/km, and 80 m long coaxial cables of the RF subsystem reduce the weight from 6.8 kg to a few hundred grams using optical fibers.

Still, in IFE systems, the use of optical fibers provides broadband communication with connectivity [3,4]. Regarding video displays, in-flight entertainment (IFE) (and more recently in-flight entertainment and connectivity (IFEC) systems) systems provide passengers with a variety of information such as audio, video, movies, games, movements, maps, flight information, terminal/connecting flights, chats, telephones, SMS, shopping, destination information, attendant call, bathroom status, food menus, etc.

Optical fibers are also used in flight control systems due to their high transmission capacity and better reliability, as well as their immunity to electromagnetic interference, high-intensity radiated fields (HIRF), and lightning [5]. In navigation systems, optical fibers can be used in aircraft to transmit crucial information quickly and accurately; in security systems, optical fibers allow the reliable transmission of data from sensors, such as fire detectors and fuel gauges, to the cabin, allowing timely monitoring and necessary actions [5]. Another contribution of optical fibers in aviation is the concept of fly-by-light [6], an evolution of fly-by-wire that offers many potential benefits, such as reducing the weight of the aircraft. In addition, fly-by-light is very efficient due to it being electronically controlled by computers that manage the autopilot system and aircraft system. Another advantage of fly-by-light is that does not generate an "electromagnetic footprint", which is used by missiles and other military systems to track the aircraft. In this context, could optical fibers be used for energy transmission?

The transmission of power in the form of light is known as power-by-light [7], which can be achieved through space, air, or optical fibers. This concept has been used to power drones in the air [8,9].

When optical fiber is used to transmit power, the technique is better known as power-over-fiber (PoF) [10]. Since PoF was introduced in the 1970s, many types of applications have become possible. Recently, PoF has also been used to power drones, 5G base stations, and radio-over-fiber [11].

Some studies mention different uses of PoF in aircraft applications. In [12], the study discusses the efficiency of a power-by-light power supply system for avionics applications. In [13] is presented a throttle level angle sensing system that utilizes a capacitance-based rotary position transducer that is powered and interrogated via light from a single multi-mode optical fiber. In [14], the ASHLEY Project (Avionics Systems Hosted on a distributed modular electronics Large-scale demonstrator for multiple types of aircraft) declares that power-by-light technology using optical fibers is considered a strong candidate technology for the next generation of avionic systems. Power-by-light offers new opportunities for fuel gauging by removing specific intrinsic safety barriers. According to [14], the major benefits of power-by-light are the simplifying compliance to intrinsic safety regulations in fuel tanks, harvesting benefits of photonics technologies (reduced sensitivity to EMI, reduced weight and dimensions, sensor multiplexing) and reducing input and output types using a universal optical interrogator. In [15], we reported for the first time a simple experiment of IFE powered by fiber.

IFE has shown a high level of evolution in the last 30 years, according to the customer's necessities [16]. In the present study, we evaluated and tested the design of IFE using PoF in two different approaches. In the first one, a PoF system is used to power pre-loaded IFE [17]. Pre-loaded or portable IFE refers mainly to airline-issued entertainment devices that are pre-loaded with entertainment content. However, in this study, the pre-loaded IFE proposal is different from that used in practice, since in commercial systems the pre-loaded IFE consists of a tablet that is generally not attached to the back seat. In our approach, we used just a single fiber to supply the energy to the IFE monitor; no extra fiber is necessary to transmit the video information to the IFE monitor. In the second approach, a PoF system is used to power the IFE video monitor. In this approach, an extra fiber is necessary to transmit the information to the IFE video monitor and corresponds to a new IFE generation technology. In the experimental demonstration, a laser with an optical power of 12 W operating at 808 nm was used. Furthermore, we used low- and high-power GaAs photovoltaic converters, 50 m of 62.5 and 105-micron core optical fibers, an optical transmitter and receiver, and video monitors, respectively, in the first and second case to carry out the experiments. All devices used in this demonstration were off-the-shelf. This system demonstrates that PoF has the potential to reduce the weight of aircraft through the use of optical fibers to replace part of the cables and copper wires, which are heavier and more susceptible to noise and electromagnetic interference.

The application described in this study is not related to critical applications on aircraft, such as flight control systems, navigation systems, sensor systems, etc. However, it is related to entertainment systems that currently represent a relevant function in commercial aircraft. In addition, the weight reduction affects other functions of aircraft. In addition, we describe applications where the video monitor and optical receiver (that is part of the communications system) were powered by the power-over-fiber system proposed in this study.

2. Methods and Materials

2.1. Optical Links and Energy Converter Circuits for Use in PoF-IFE

Figure 1 illustrates the signal information and power connection scheme for individual assistance in an in-flight entertainment system. Using fiber to the seat (fiber-to-the-seat) could eliminate the intermediate boxes traditionally used in a system based on copper wires [5]. In this scheme, the PoF power and the IFE information signal are transmitted by individual fibers to a transition box placed below the seat where the optical to electrical conversion of the PoF to the IFE takes place, going from there to the video monitor placed in the back seat. Multimode fibers with a 50-micron core are typically used in optical fiber-based IFEs.

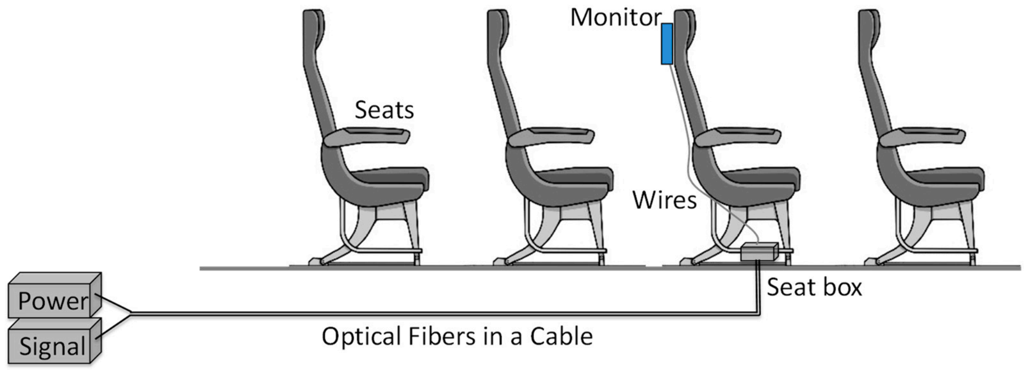

Figure 1. Signal and power connection diagram for individual service in an in-flight entertainment system.

In IFEC systems, gigabit passive optical networks (G-PON) schemes can also be used, which are currently widely used in telecommunications access networks [3]. These networks are based on splitting the optical signal using optical couplers. The use of a power division scheme in PoF to serve several seats is highly desirable, but it brings challenges in using extremely high-power lasers, as well as fibers, connectors, and optical splitters that support high power. A large part of the damage at high power is attributed to the effects of power on glass–air interfaces, such as optical connector interfaces. Fiber-end-face damage is the main problem related to high-power transmission in optical fiber. In this effect, part of the optical power is absorbed by irregularities at the glass/air interface, generating heat and leading to catastrophic damage [18,19]. The theoretical CW damage threshold for the glass/air interface is ~1 MW/cm^2. The threshold is 86.5 W for a 105-micrometer core, but the laser suppliers generally recommend a much lower safety value. In addition, optical fibers terminated with conventional connectors using epoxy to bond the optical fiber in the ferrule can suffer damage due to the high power. If part of the high power is scattered into the ferrule, it can burn the epoxy, causing it to vaporize and deposit a residue on the face of the connector.

In this research, we studied an IFE system based on a PoF system using an optical fiber length connecting a high optical source (HPOS) to an energy transformation unit (ETU) that represents the seat box in Figure 1. In Figure 2a,b, we show the two PoF-IFE schemes studied in this research. In Figure 2a, the PoF-IFE system uses pre-loaded IFE and in Figure 2b, the PoF-IFE system uses an extra fiber to transmit the video information to the IFE monitor.

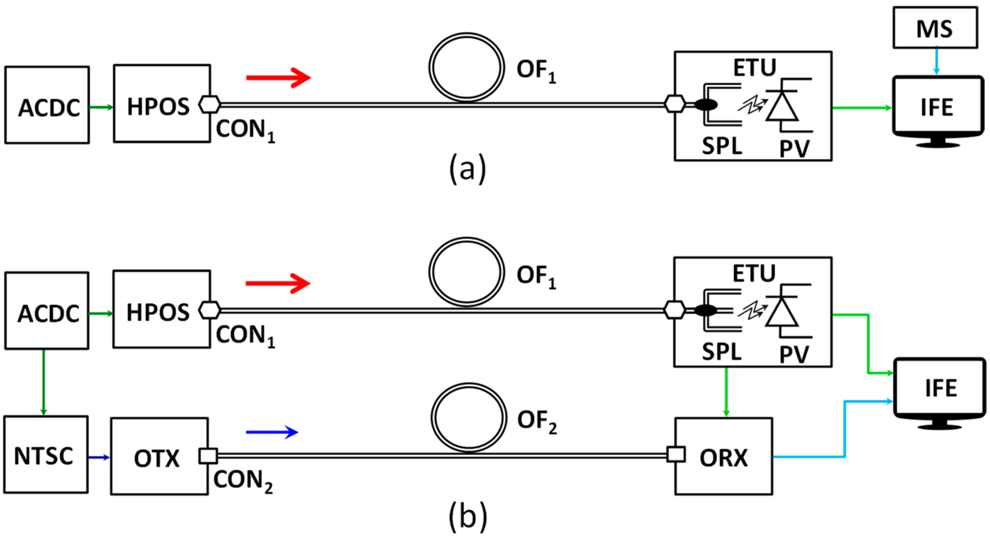

Figure 2. PoF-IFE systems schemes studied in this research. (**a**) PoF-IFE system using pre-loaded IFE and (**b**) PoF-IFE system using an extra fiber to transmit the video information to the IFE monitor. The block identifications are as follows: ACDC—alternate to continuous electrical power supply, HPOS—high power optical source, NTSC—video generator, OTX—optical transmitter, CON_1—HPOS optical connector, CON_2—OTX optical connector, OF_1—optical fiber to PoF, OF_2—optical fiber to video transmission, ETU—energy transformation unit, SPL—splitter, PV—photovoltaic converters, ORX—optical receiver, IFE—in-flight entertainment monitor, MS—memory stick. The red arrow represents the HPOS high power, the dark blue arrow represents the OTX video signal power, the green arrows represent the electricity supplied by ETU to ORX and IFE, and light blue arrow represents the NTSC electrical video signal from ORX to IFE.

An important aspect of PoF is the ETU's energy conversion scheme to meet different types of voltage, current, and power consumption. Figure 3 shows two configurations of ETU used in this study containing splitters and PVs to obtain voltage and current levels necessary for a specific load power [10]. Furthermore, PVs must be specified regarding their maximum optical input power. Above this power level, the efficiency of these devices drops with the increase in temperature caused by high power [20,21].

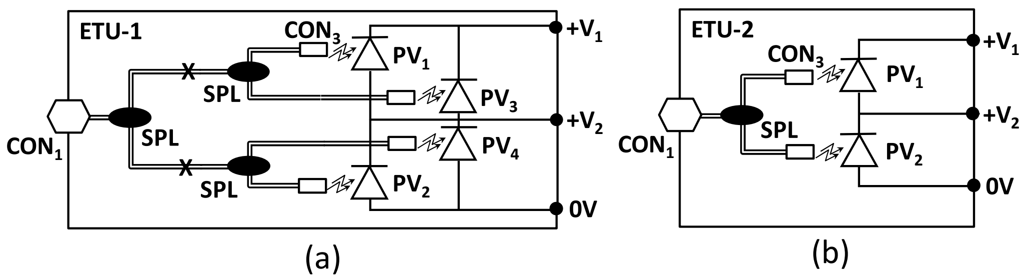

Figure 3. ETU schemes studied in this research. (**a**) ETU-1: three splitters connected in series dividing the input power into four branches that power two PVs connected in series with two in parallel, and (**b**) ETU-2: one splitter dividing the input power into two branches powering two PVs connected in series.

2.2. Design of PoF Systems and Circuits for IFE and the Specifications of Devices

Using the PoF power budget equations described in [10], we can evaluate the real possibility of this application for both schemes shown in Figure 2 using the ETU types of Figure 3. According to [10], we have the following:

$$P_{PV} = P_{Load} / \eta_{PV} \tag{1}$$

$$P_{HPOS} = P_{PV} / \alpha_{\text{Fiber}} . \alpha_{\text{Conn}} . \alpha_{\text{Spl}} \tag{2}$$

$$\alpha_{\text{Fiber}} = 10^{(-\text{L}.\alpha_{\text{FiberdB}}/10)} \tag{3}$$

$$\alpha_{\text{Conn}} = 10^{(-\alpha_{\text{ConndB}}/10)} \tag{4}$$

$$\alpha_{\text{Spl}} = 10^{(-\alpha_{\text{SpldB}}/10)} \tag{5}$$

where P_{PV} is the optical power in the PV input in W, P_{Load} is the electrical power of the load, η_{PV} is the PV efficiency, P_{HPOS} is the HPOS output power, L is the fiber length in km, $\alpha_{FiberdB}$ is the fiber attenuation in dB/km, α_{ConndB} is the total connector loss, and α_{SpdB} is the total splitter loss.

Considering the specification to use off-the-shelf devices in this research, we adopted the specifications of similar commercial video monitors but for other applications, the first one with 2.2 W of power consumption [22] for the scheme in Figure 2b and a digital picture frame for the second scheme in Figure 2a (model IT-Blue Max-703 from Alinee), and an optical receiver of 2.5 W [23]. We calculated the link power budget using commercial PVs made with currently available materials, GaAs and Si. The parameters for the link calculation are PV efficiency, that for GaAs PV is 50% (@808 nm) [24,25], and that for Si PV is 26.8% (@975 nm) [26]. The other parameters are α_{FiberdB} = 2 dB/km @ 808 nm and 1.6 dB/km @ 975 nm [27], L = 50 m, α_{ConndB} = 0.5 dB [28], and α_{SpdB} = 1.2 dB [29]. Using these values in Equation (1)–(5) results in the values shown in Tables 1 and 2. The power budget of the video communication link will not show because it is a commercial transmission and receiver kit [23]. This system allows the transmission of NTSC, PAL, and SECAM video signals in a digital way. Tables 1 and 2 summarize the power budget calculations for the PoF-IFE link schemes in Figure 2a,b and for the ETU schemes in Figure 3a,b.

Table 1. Link power budget parameters of the PoF-IFE system using pre-loaded IFE.

Parameter	ETU-1		ETU-2	
PV Type	**Si (975 nm)**	**GaAs (808 nm)**	**Si (975 nm)**	**GaAs (808 nm)**
Load Consumption (W)	2.2	2.2	2.2	2.2
PV efficiency (%)	26.8	50	26.8	50
P_{PV} (W)	8.2	4.4	8.2	4.4
PV quantity	4	4	2	2
Power by PV	2.05	1.1	4.1	2.2
α_{Fiber} (dB/km)	1.6	2.0	1.6	2.0
α_{Conn} (dB)	1.0	1.0	1.0	1.0
α_{Spl} (dB)	2.4	2.4	1.2	1.2
P_{HPOS} (W)	18.3	9.8	13.3	7.4

We specified the HPOS with a 15-Watt laser module at 808 nm [30] for both types of PoF links. For the high power measurements detailed in the Section 3, we used an optical power meter, model 1835-C, and detector 818T-30/CM from MKS Instruments, Inc., Andover, MA, USA.

In the video optical link, we used a 62.5-micron optical fiber operating in the wavelength of 1310 nm, and the maximum distance of operation of the commercial transmission and receiver kit is 500 m.

Table 2. Link power budget parameters for the PoF-IFE system using an extra fiber to transmit the video signal to the IFE monitor.

Parameter	**ETU-1**		**ETU-2**	
PV Type	**Si (975 nm)**	**GaAs (808 nm)**	**Si (975 nm)**	**GaAs (808 nm)**
Load Consumption (W)	4.7	4.7	4.7	4.7
PV efficiency (%)	26.8	50	26.8	50
P_{PV} (W)	17.5	9.4	17.5	9.4
PV quantity	4	4	2	2
Power by PV	4.3	2.3	8.7	4.7
α_{Fiber} (dB/km)	1.6	2.0	1.6	2.0
α_{Conn} (dB)	1.0	1.0	1.0	1.0
α_{Spl} (dB)	2.4	2.4	1.2	1.2
P_{HPOS} (W)	39.0	20.9	29.7	15.9

Figure 4a shows the laser assembly in an aluminum box (HPOS). The laser case is mounted internally in the top plate. A heat sink and a fan (Figure 4b) are used on the external side to reduce the temperature of the laser.

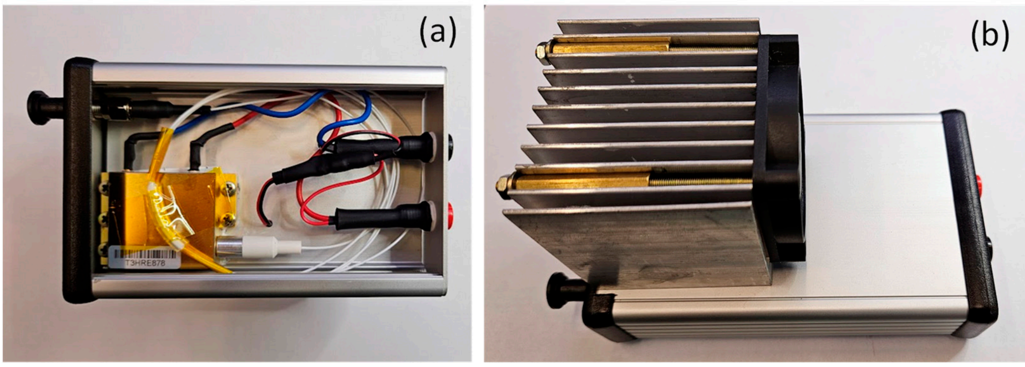

Figure 4. (**a**) Laser assembly in an aluminum box and (**b**) heat sink and a fan used in the external side to reduce the temperature of the laser.

Figure 5a,b show the ETU assembly in an aluminum box for the ETU-1 and ETU-2 schemes, respectively. In the ETU-1 scheme, we used the PV model AFBR-POC406L [24]. For this model, the maximum input power is 1.5 W. In the ETU-2 scheme, we used the PV model AFBR-POC306A1 [25]. For this model, the maximum input power is 6.0 W. The PVs are mounted internally on the top plate to reduce the temperature. In the assembly shown in Figure 5a, each splitter was connected with the other using splices. These splitters have a fiber diameter of 220 microns and because of this, the splices have to be carried out using a special machine splicer, which in this case was the splicer model Fujikura FSM-100P (Fujikura Ltd., Tokyo, Japan). An important note is that is very difficult to find splice machines in the market that make splices for optical fibers with diameters larger than 125 microns. In addition, the exact point of arc fusion must be tested to find the exact arc level before the splices are carried out. The splitters were also mounted internally in the top plate to reduce the temperature inside them.

Figure 6 shows the transmission and reception parts of the schemes in Figure 2. Figure 6a,c correspond to the power transmitter side and Figure 6b,d correspond to the power receiver side.

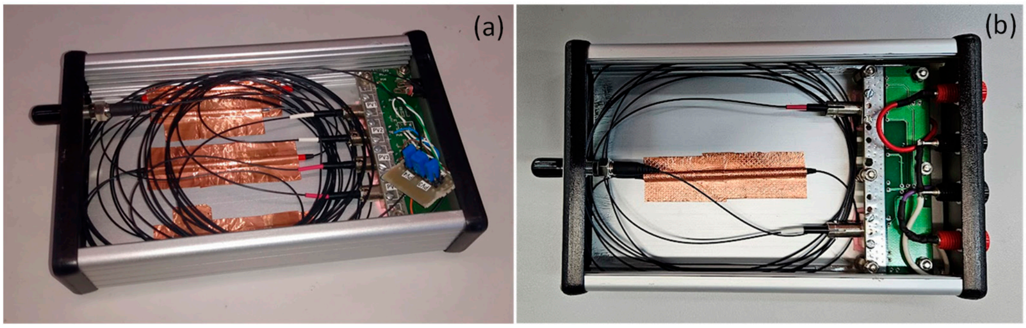

Figure 5. (**a**) ETU assembling for the scheme in Figure 3a; (**b**) ETU assembling for the scheme in Figure 3b.

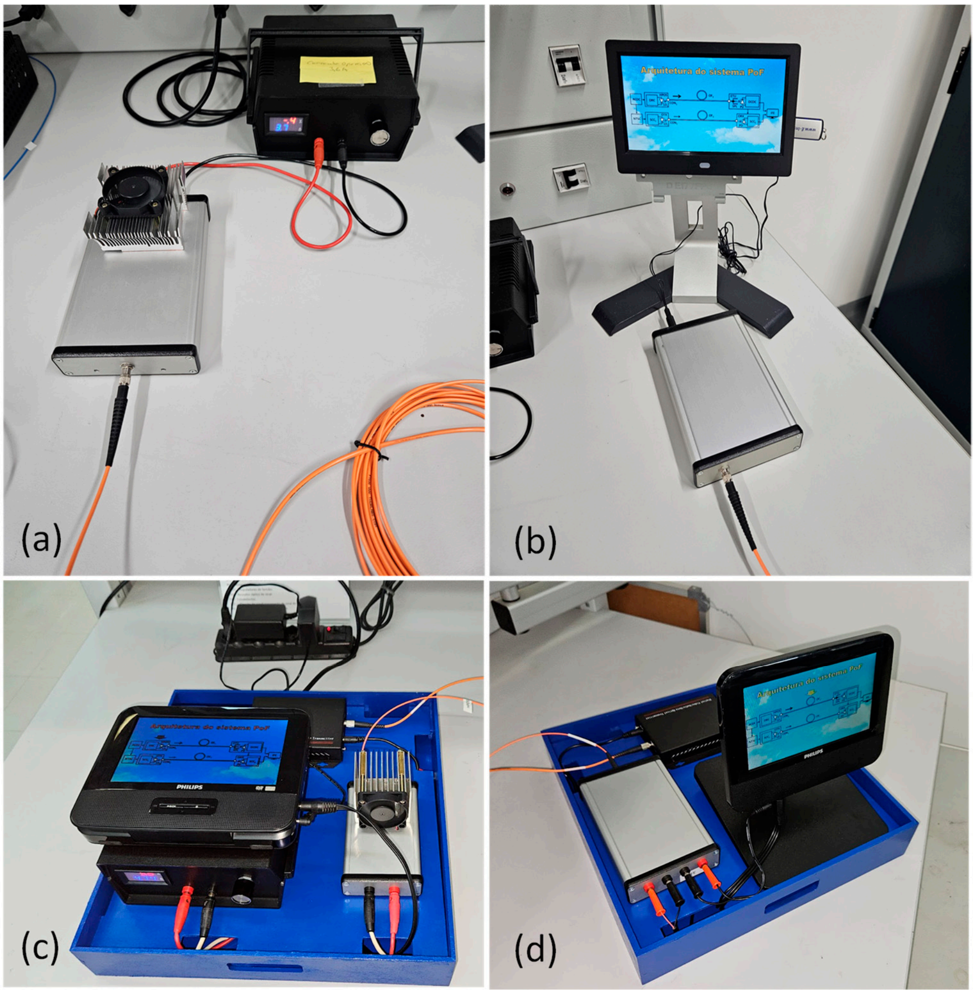

Figure 6. (**a**) ACDC—electrical power supply and HPOS—high power optical source; (**b**) ETU-1—energy transformation unit and IFE—in-flight entertainment monitor; (**c**) ACDC—electrical power supply, HPOS—high power optical source, and OTX—optical transmitter; (**d**) ETU-2—energy transformation unit, ORX—optical receiver, and IFE—in-flight entertainment monitor.

Figure 7 shows the PoF-IFE systems studied, where (a) is the PoF-IFE system using pre-loaded IFE and (b) is the PoF-IFE system using an extra fiber to transmit the video information to the IFE monitor.

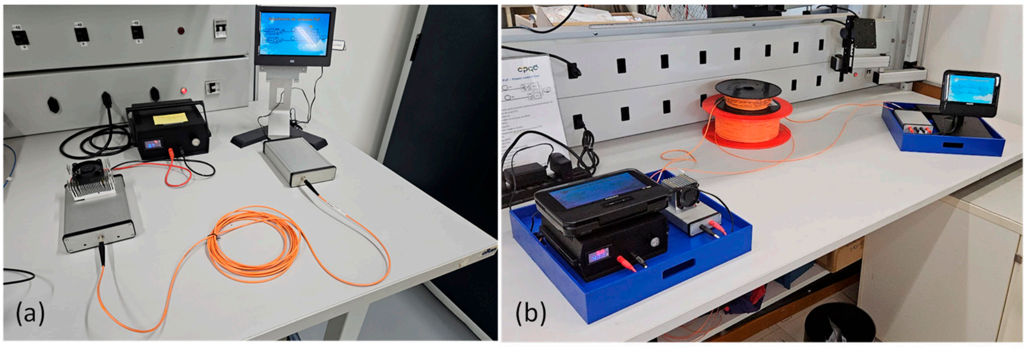

Figure 7. (**a**) PoF-IFE system using pre-loaded IFE; (**b**) PoF-IFE system using an extra fiber to transmit the video information to the IFE monitor.

3. Results

In this section, we show the results of ETU characterization and the performance of the PoF-IFE systems. We clarify that only ETU-1 was initially evaluated. Based on the results obtained, we evaluated ETU-2. The ETU-1 scheme (Figure 3a) presented an insertion loss (1 connector, 2 splices, and 2 splitters) of 4.13 dB, which is 0.76 dB worse than the theoretical value used in the power budget calculation. The ETU-2 scheme (Figure 3b) presented an insertion loss (1 connector and 1 splitter) less than 0.5 dB, which is 1.7 dB better than the theoretical value used in the power budget calculation.

Figure 8a,b show the electrical power versus load characterizations for ETU-1 and ETU-2, respectively.

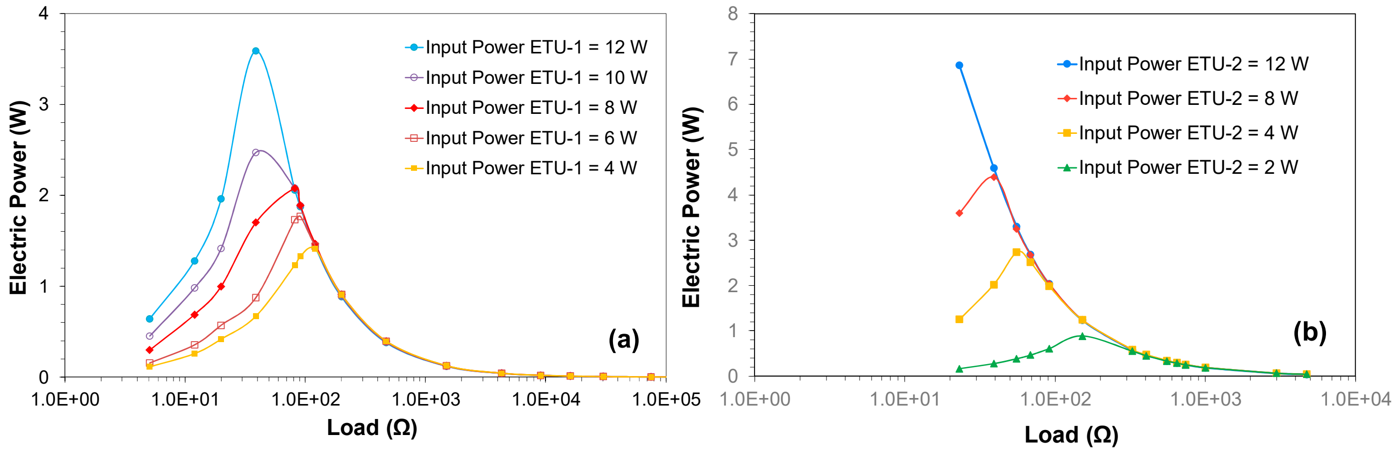

Figure 8. Electrical power versus load characterizations for (**a**) ETU-1 and (**b**) ETU-2.

Figure 9a,b show the optimum load versus optical power characterizations for schemes ETU-1 and ETU-2, respectively. Figures 8 and 9 show an important characteristic of PV, that is, for a given load or optical input level, the electric output is maximum at that point. At that point, there is only one particular combination of current and voltage and, therefore, only one optimum load resistance [31]. It is possible to use voltage regulation or operate at or close to the electric output maximum using MPPT (maximum power point tracking) [31], which is a logical electronic circuit whose function is to track the highest power point of the photovoltaic array to which it is connected, and in a constant way. In PoF systems, the power transfer efficiency from the PVs depends on the amount of available light, temperature, and the electrical characteristics of the load. As these conditions vary, the optimum load characteristic that yields the highest power transfer also changes. In MPPT, the circuits can be designed to present optimal loads to the PVs.

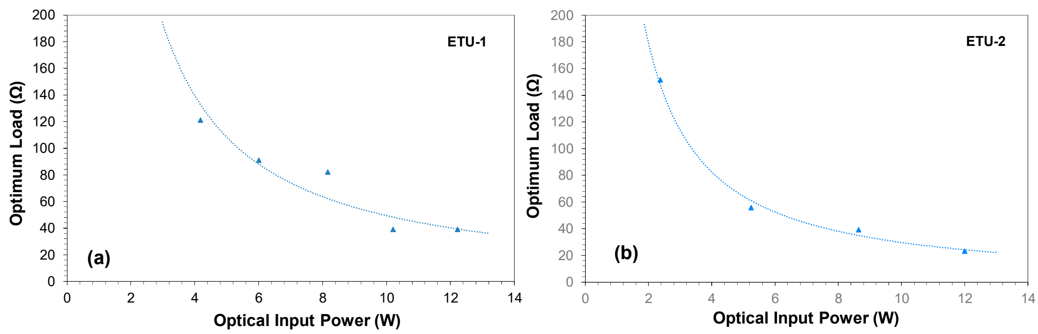

Figure 9. Optimum load versus optical input power characterizations for schemes (**a**) ETU-1 and (**b**) ETU-2.

Figure 10 shows the electrical output power versus optical input power characterizations for schemes ETU-1 and ETU-2. It can be observed that the ETU-2 scheme is approximately twice as efficient as ETU-1. This is expected due to the use of two splitters and respective fiber splices that cause the increase in the insertion loss and consequently, the reduction in the power delivered to the PVs.

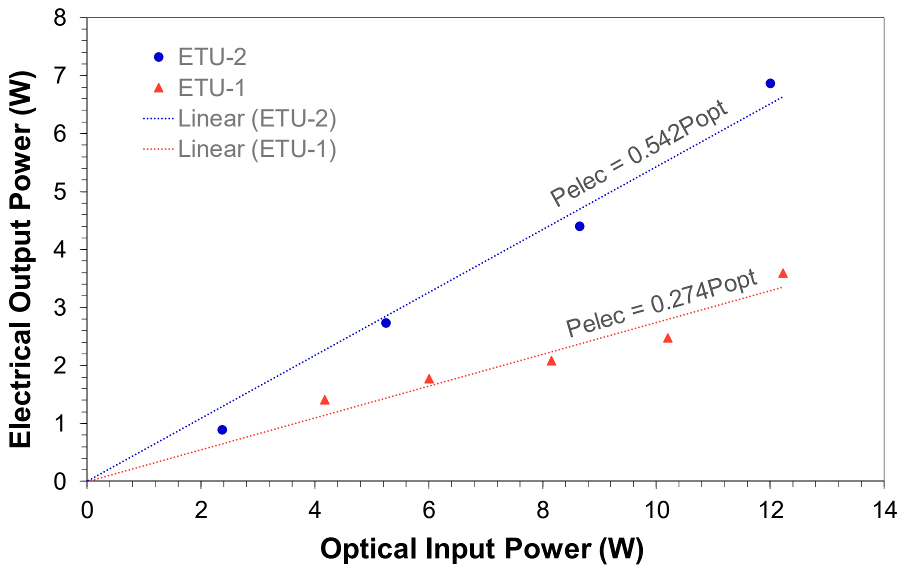

Figure 10. Electrical output power versus optical input power characterizations for ETU-1 and ETU-2.

Figure 11a,b show the voltage versus current characterizations at some optical input power levels for schemes ETU-1 and ETU-2, respectively. Considering the nominal power of the IFE monitors, ETU-1 has power only to attend the preloaded IFE system (2.2 W) and the ETU-2 scheme can attend the IFE system with the IFE monitor and optical receiver. The voltage versus current curve for ETU-1 is typical of PVs fabricated with 4 or 5 PN junctions [32] and ETU-2 is typical of PVs fabricated with 6 PN junctions [20].

The PoF-IFE systems using pre-loaded IFE and PoF-IFE systems using an extra fiber to transmit the video information to the IFE monitor worked for many hours, and the performance was according to the expectation. No degradation of video quality was observed in this period. In the first scheme, the HPOS operated with P_{HPOS} = 10 W, and in the second one with P_{HPOS} = 12 W. The maximum temperature reached on the PV case for ETU-2 was 50 °C. A supplementary short Video S1 is available online regarding these PoF-IFE systems working at our laboratory.

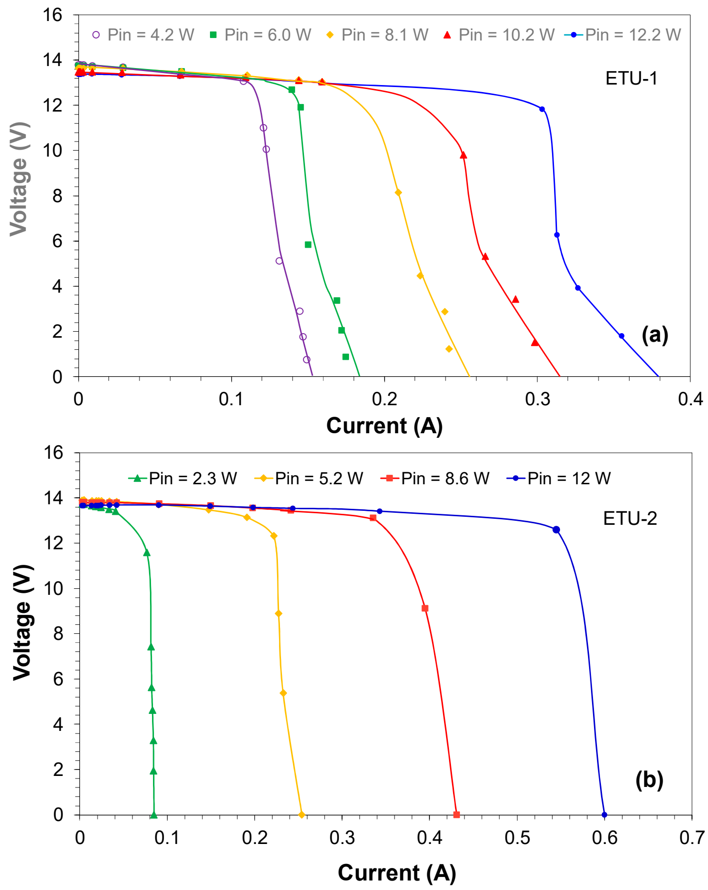

Figure 11. Voltage versus current characterization at some optical input power levels for: (**a**) ETU-1; (**b**) ETU-2.

4. Discussion

In search of weight reduction in aircraft, we proposed in this study the use of optical fibers to transmit a video signal and energy to replace the part of the copper cables still used for this purpose specifically for in-flight entertainment systems. To demonstrate this concept, some calculations of power-over-fiber links for aircraft applications were demonstrated. Parameters from commercial elements were used such as high-power lasers, PVs, connectors, fibers, and splitters. However, given the first practical demonstration (proof of concept) and availability, for the IFE video monitors we used simpler commercial elements and not necessarily the video monitors used commercially on aircraft. The direct consequence is the fact that in this proof of concept, the load power values are lower than in a commercial monitor specific to IFE, where the power is greater than 10 W [33].

Two types of optical systems were proposed to demonstrate the proof of concept. In the first one, a PoF system is used to power pre-loaded IFE. As we commented before, pre-loaded IFE refers mainly to airline-issued entertainment devices that are pre-loaded with entertainment content. In our demonstration, the pre-loaded IFE is different from that used in practice, since in commercial systems the pre-loaded IFE consists of a tablet that is not usually attached to the back of the seat. In the second approach, a PoF system is used to power and transmit online IFE video signals. In this approach, an extra fiber is necessary to transmit the information to the IFE monitor and corresponds to a new IFE generation technology. In both systems, we adopted a link distance of 50 m to simulate correctly a maximum distance from a transmission unit to a seat equipped with video monitors.

The studied and tested links were point-to-point, but to reduce the number of fibers used, a point-to-point topology would be interesting, such as a PON (passive optical network) system used in telecommunications. This configuration would allow the service of some seats with the same fiber but would require lasers with greater optical power, fibers with larger core diameters, and robust optical connectors, which would require careful study from the point of view of high optical power usability.

During the initial tests developed in this research, it was necessary to disconnect and connect the optical connectors after shutting down the optical power. In some cases, the connector's end faced caught dust, which caused a total connector failure when high power was turned on. In this case, it was necessary to change them. In addition, as we commented before since the splitters used in the ETUs have fibers with core diameters of 220 microns, it was very complex to splice them. Is important to observe that it is very difficult to find splice machines in the market that make splices for optical fibers, such as a splicer for diameters larger than 125 microns. In addition, the exact point of arc fusion intensity must be tested before the splices are made. The splitters and PVs were also mounted internally in the top plate to reduce the temperature.

On the other hand, assembling the PVs, splitters, and input optical connectors in an aluminum box ensured that the temperature in the PVs did not exceed 50 °C. The maximum operating temperature of PVs is 85 °C.

The analysis of the experimental results mainly shows that the use of more than one splitter substantially increases the intrinsic insertion loss, which leads to a loss in efficiency of the power transformation units. This was the case of the ETU-1 scheme, where losses due to the connector, splices, and splitters were 4.13 dB. In ETU-1, the connection between the splitter fibers was made by fusion splices. We use splitters with 200-micron core fibers to better support high optical power. As we used splitters with fiber cores greater than 125 microns, it was necessary to use a special splicing machine. Even using this special splicing machine, making the splices was problematic and possibly introduced additional losses. In addition, when it comes to using devices at high power, a possible degradation of optical connectors over time cannot be ruled out. In the experiments, we handled open connectors with the utmost care due to the possibility of them collecting dust.

In the ETU-2 scheme, there were no fiber splices, and the losses (intrinsic) with only one splitter were less than 0.5 dB. Given these circumstances, the ETU-1 scheme was chosen be used in the pre-loaded PoF-IFE system with the HPOS operating at 10 W, and the ETU-2 scheme was chosen to be used in PoF-IFE system with additional fiber with the HPOS operating at 12 W. It is important to note that at this power level the PVs in each ETU operated with input optical power below the maximum allowed (1.5 W for ETU-1 and 6 W for ETU-2) [24,25].

5. Conclusions

Since the use of optical fibers is increasing in modern aircraft in sensing, control, and communication due to their high transmission capacity, better reliability, as well as their immunity to electromagnetic interference, high-intensity radiated fields, and lightning, this paper presented a new functionality in aircraft, using optical fiber to replace part of the copper cables to transmit power. Specifically, this study described a video and power transmission system using optical fibers for in-flight entertainment (IFE) system application. We described the benefits and the limitations of this application, and we performed two practical experiments to demonstrate it. It used off-the-shelf devices, such as 15-Watt semiconductor lasers operating at 808 nm, GaAs photovoltaic converters, optical transmitter, optical receiver, and video monitors in the experiments. The power and video signals were transmitted using two 50-m length multimode fibers. In addition, we proposed and tested two types of energy transformation units (ETU), which are responsible for supplying electrical energy to the IFE video monitor and the optical fiber receiver.

For future potential power-over-fiber applications, there are two considerations: (i) the conversion efficiency of electric–optic–electric process has been increasing in recent years, and we foresee much higher total efficiencies in the next years; and (ii) weight reduction (copper versus fiber optics cables) and an increased throughput of data would be an important asset for the trade-off.

Currently, there is low efficiency in terms of the process of energy transmission and conversion. This is a typical situation in PoF applications, and many complementary studies must be carried out to determine if it makes sense to use PoF in aircraft. For example, the computation of cost of weight (COW) is a primary parameter for determining the associated cost impact when weight is added to or removed from a spacecraft. In addition, we can imagine using this application not just on a large plane where it may be needed to power hundreds of video monitors in a practical application, which means too much energy would be wasted, but in different types of planes including new electric aircraft, for example, e-VTOL (electric vertical take-off and landing) aircraft.

Nevertheless, this demonstration paves the way for the development of diverse aeronautical solutions in the most diverse systems, since the main characteristics of fiber optic technology have shown that this is an 'enabling element' for the future of aviation, where we will undergo paradigm changes in aerodynamics, materials, and massive electrification.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/photonics11070627/s1, Video S1: Video showing the PoF-IFE systems working at our laboratory.

Author Contributions: Conceptualization, A.B.d.S. and J.B.R.; methodology, L.M.W.; validation, L.M.W. and M.P.d.O.; investigation, J.B.R. and F.R.B.; resources, A.B.d.S.; data curation, J.B.R. and F.R.B.; writing—original draft preparation, J.B.R.; writing—review and editing, A.B.d.S., F.R.B., M.P.d.O. and L.M.W.; project administration, A.B.d.S.; funding acquisition, A.B.d.S. All authors have read and agreed to the published version of the manuscript.

Funding: The authors thanks Embrapii grant PCPQ-2306.0111 and the National Council for Scientific and Technological Development (CNPq), grants 440220/2021-1, 303791/2021-7, and 302755/2023-3.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors wish to thank Carla C. Furoni for all administrative support and Pedro J. Nagano, Luiz A. R. Nerosky, Jose Juliano Fioretto, and João Roberto Nogueira Junior for all technical support.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Careless, J. Trends and Advances in Embedded Avionics Systems: An ATR Roundtable. Aerospace TechReview. 2022. Available online: https://aerospacetechreview.com/trends-and-advances-in-embedded-avionics-systems-an-atr-roundtable/ (accessed on 6 May 2024).
2. Engineering ToolBox. 2001. Available online: https://www.engineeringtoolbox.com/density-solids-d_1265.html (accessed on 6 May 2024).
3. Saadaoui, H.; Bacou, A.; Rebiere, Y.; Fracasso, B.; Morvan, M. Broadband optical network design for the future aircraft cabin. *Opt. Contin.* **2022**, *1*, 719–737. [CrossRef]
4. Bellamy, W., III. On-Demand Cabins: The New In-Flight Entertainment, Avionics Today. 2015. Available online: https://interactive.aviationtoday.com/on-demand-cabins-the-new-in-flight-entertainment/ (accessed on 6 May 2024).
5. Koon, J. How Fiber Optics Will Propel Future Avionics, Avionics Today. 2020. Available online: http://interactive.aviationtoday.com/how-fiber-optics-will-propel-future-avionics/ (accessed on 6 May 2024).
6. Tameh, T.A.; Sawan, M.; Kashyap, R. Optical sensors for fly-by-light flight control systems. In Proceedings of the 2016 IEEE Avionics and Vehicle Fiber-Optics and Photonics Conference (AVFOP), Long Beach, CA, USA, 31 October–3 November 2016; pp. 295–296. [CrossRef]
7. Algora, C.; García, I.; Delgado, M.; Peña, R.; Vázquez, C.; Hinojosa, M.; Rey-Stolle, I. Beaming power: Photovoltaic laser power converters for power-by-light. *Joule* **2022**, *6*, 340–368. [CrossRef]
8. Mohammadnia, A.; Ziapour, B.M.; Ghaebi, H.; Khooban, M.H. Feasibility assessment of next-generation drones powering by laser-based wireless power transfer. *Opt. Laser Technol.* **2021**, *143*, 107283. [CrossRef]
9. Natsuki, S.; Kobatake, T.; Masson, D.; Fafard, S.; Matsuura, M. Optically Powered and Controlled Drones Using Optical Fibers for Airborne Base Stations. *Photonics* **2022**, *9*, 882. [CrossRef]

10. Rosolem, J.B. Power-over-fiber applications for telecommunications and for electric utilities. In *Optical Fiber and Wireless Communications*; IntechOpen: London, UK, 2017. [CrossRef]
11. Matsuura, M. Recent Advancement in Power-over-Fiber Technologies. *Photonics* **2021**, *8*, 335. [CrossRef]
12. Sherman, B.D.; Mendez, A.J.; Morookian, J.M. Efficiency of a 5V/5-mW power by light power supply for avionics applications. In *Fiber Optic Systems for Mobile Platforms IV, Proceedings of the SPIE Microelectronic Interconnect and Integrated Processing Symposium, San Jose, CA, USA, 1 February 1991*; Proc. SPIE 1369; SPIE: Bellingham, WA, USA, 1991. [CrossRef]
13. Spillman, W.B.; Crowne, D.H.; Woodward, D.W. Optically powered and interrogated rotary position sensor for aircraft engine control applications. *Opt. Lasers Eng.* **1992**, *16*, 105–118. [CrossRef]
14. CORDIS. Final Report Summary—ASHLEY—Avionics Systems Hosted on a Distributed Modular Electronics Large Scale dEmonstrator for Multiple tYpe of Aircraft; Community Research and Development Information Service (CORDIS): 2017. Available online: https://cordis.europa.eu/project/id/605442/reporting/it (accessed on 16 May 2024).
15. Rosolem, J.B.; Nogueira Júnior, J.R.; Bassan, F.R.; Furoni, C.C.; dos Santos, A.B.; Wollinger, L.M.; Nagano, P.J.; de Oliveira, M.P.; Nerosky, L.A.R.; Fioretto, J.J. Power-over-Fiber Applied for In-Flight Entertainment System. In Proceedings of the 6th Optical Wireless and Fiber Power Transmission Conference (OWPT2024), Online, 23–26 April 2024.
16. Jin, M.J.; Kim, J.K. Customer adoption factors for in-flight entertainment and connectivity. *Res. Transp. Bus. Manag.* **2022**, *43*, 100759. [CrossRef]
17. Preston, A. The Incredible Evolution of In-Flight Entertainment. Key.Aero. 2023. Available online: https://www.key.aero/article/incredible-evolution-flight-entertainment (accessed on 16 May 2024).
18. Mann, G.; Jurke, M.; Zoheidi, M.; Eberstein, M.; Krüger, J. Influence of core diameter and coating material on nanosecond laser-induced damage threshold of optical multimode fibers. *J. Optoelectron. Adv. Mater.* **2010**, *12*, 711–714. [CrossRef]
19. Seo, K.; Nishimura, N.; Shiino, M.; Yugushi, R.; Sasaki, H. Evaluation of high-power endurance in optical fiber links. *Furukawa Rev.* **2003**, *24*, 17–22.
20. Fafard, S.; Masson, D.P. Perspective on photovoltaic optical power converters. *J. Appl. Phys.* **2021**, *130*, 160901. [CrossRef]
21. Fafard, S.; Masson, D.; Werthen, J.G.; Liu, J.; Wu, T.C.; Hundsberger, C.; Schwarzfischer, M.; Steinle, G.; Gaertner, C.; Piemonte, C.; et al. High-Efficiency Photovoltaic Power Converters and Application to Optical Power Transmission. In Proceedings of the 26th Microoptics Conference (MOC), Hamamatsu, Japan, 26–29 September 2021; pp. 1–2. [CrossRef]
22. Phillips. PD7012/37—Philips Portable DVD Player. Available online: https://www.documents.philips.com/assets/20231202/651d40d8ab804c29b6a4b0cc01139fe4.pdf (accessed on 6 May 2024).
23. Primeda-Telecom. JL-1V1A—Video/Audio/Data over Fiber Media Converters. Available online: http://www.primeda-telecom.com/product_view_746.html (accessed on 6 May 2024).
24. Broadcom. AFBR-POC406L—Optical Power Converter 6VDC, ST Port. Available online: https://www.broadcom.com/products/fiber-optic-modules-components/industrial/optical-power-components/optical-power-converters/afbr-poc406l (accessed on 6 May 2024).
25. Broadcom. AFBR-POC306A1—Optical Power Converter 3W, ST Port. Available online: https://www.broadcom.com/products/fiber-optic-modules-components/industrial/optical-power-components/optical-power-converters/afbr-poc306a1 (accessed on 6 May 2024).
26. MH GoPower. YCH-H003—A Novel Electrical Power Delivery Technology/YCH Series MIH Photovoltaic Power Converter. Available online: http://www.mhgopower.com/laser_pof_YCHPPC.html (accessed on 6 May 2024).
27. Thorlabs. FG105LCA-CUSTOM—0.22 NA Silica Core, Glass Clad Multimode Optical Fiber, Step Index. Available online: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=6838&pn=FG105LCA (accessed on 6 May 2024).
28. Thorlabs. Step-Index Multimode Fiber Optic Patch Cables: SMA to SMA. Available online: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=351 (accessed on 6 May 2024).
29. Thorlabs. TM105SS1B—Fiber Optic Couplers for Optogenetics. Available online: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=7800&pn=TM200SS1B (accessed on 6 May 2024).
30. Skyera. TY-808+/-03NM-15.0W-25C-105-0.22NA-15W—808 nm 105 µm Multi-function Laser Diode Module. Available online: http://www.skyeralaser.com/products_show.asp?s_id=361 (accessed on 6 May 2024).
31. Broadcom. Optical Power Components Optimizing Optical Power Converter Output, Application Note. Available online: https://docs.broadcom.com/doc/AFBR-POCxxxL-AN (accessed on 6 May 2024).
32. Fafard, S.; Proulx, F.; York, M.C.; Richard, L.S.; Provost, P.O.; Arès, R.; Aimez, V.; Masson, D.P. High-photovoltage GaAs vertical epitaxial monolithic heterostructures with 20 thin p/n junctions and a conversion efficiency of 60%. *Appl. Phys. Lett.* **2016**, *109*, 131107. [CrossRef]
33. AeroExpo. Plugin Displays. Available online: https://pdf.aeroexpo.online/pdf/rosen-aviation/catalog-2011/173330-721.html#open6118 (accessed on 6 May 2024).