APPLICATIONS

One-watt fiber-based power-by-light system for satellite applications

Rafael Peña and Carlos Algora

ABSTRACT

In this work, a fiber-based optical powering (or power-by-light) system capable of providing more than 1 W is developed. The prototype was used in order to power a shunt regulator for controlling the activation and deactivation of solar panels in satellites. The work involves the manufacture of a light receiver (a GaAs multiple photovoltaic converter (MPC)), a power conditioning block, and a regulator and the implementation and characterization of the whole system. The MPC, with an active area of just 3.1 mm^2, was able to supply 1 W at 5 V with an efficiency of 30%. The maximum measured device efficiency was over 40% at an input power (P_{in}) of 0.5 W. Open circuit voltage over 7 V was measured for P_{in} over 0.5 W. A system optoelectronic efficiency (including the optical fiber, connectors, and MPC) of 27% was measured at an output power (P_{out}) of 1 W. At $P_{\mathrm{out}} = 0.2$ W, the efficiency was as high as 36%. The power conditioning block and the regulator were successfully powered with the system. The maximum supplied power in steady state was 0.2 W, whereas in transient state, it reached 0.44 W. The paper also describes the characterization of the system within the temperature range going from −70 to +100 °C.

KEYWORDS

optical powering systems; photovoltaic converters; power supply for satellite equipment

1. INTRODUCTION

Power by light (PBL) is an emerging technology that can replace conventional copper wire-based powering systems in applications or regions that have strict safety requirements [1,2]. Such applications or regions are usually called “exclusion regions” and are classified in the presence of a risk of explosion or in areas of high electromagnetic noise, such as high-voltage lines, refineries, mines, fuel tanks, satellites, aircrafts, nuclear plants, and telephone systems [3]. PBL technology has also been tested for powering implantable devices inside the human body [4].

Typical optical powering links consist of a light source (usually a laser diode), a transmission medium (an optical fiber or the air), and a light receiver (a photovoltaic (PV) converter [5]). The light source converts the electrical power from a non-problematic region into optical power, which is sent by means of the transmission medium to the light receiver. The light receiver transforms the light power into electricity and powers equipment in the exclusion region.

Power-by-light systems provide a powering link that is insensitive to electromagnetic noise and is electrically isolated between the ends. A risk of explosion is greatly reduced because of the absence of sparks in these systems.

In this work, an optical fiber-based PBL system capable of providing more than 1 W at a voltage of up to 12 V is developed. The prototype was used to power a shunt regulator for switching solar panels in a satellite PV array, which was developed in an ad hoc fashion. In this application, the lack of interference with the PV array control link was compulsory. PBL systems can ensure that this important requirement is met.

The power receiver used in the system was a GaAs multiple photovoltaic converter (MPC) manufactured at the laboratory of the Instituto de Energía Solar, Universidad

Politécnica de Madrid (Figure 1). The MPC consisted of a pie-shaped converter that comprised six sub-cells monolithically connected in series on a semi-insulating substrate. The high-voltage (open circuit voltage up to 7.1 V) and high-power (up to 1 W) properties were remarkable for such a small 3-mm^2 converter. To the best of our knowledge, devices with such properties have not previously been reported in the literature.

This work also involves the development and characterization of a powered shunt regulator and a power conditioning block. The latter was capable of efficiently boosting the MPC output voltage to 12 V and providing current peaks of up to 1 A.

2. DEVELOPMENT OF MULTIPLE PHOTOVOLTAIC CONVERTERS FOR HIGH-POWER APPLICATIONS

The GaAs MPCs are the most commonly used receivers in PBL systems because of their high efficiency at high-power levels. The MPC output voltage can be adjusted to that of the powered circuit [6–8] (between 3 and 12 V, in most cases). These requirements are not met by other data photoreceivers used in optical data communications systems.

As mentioned, the MPC developed in this work is made up of six series-connected sector-shaped sub-cells (Figure 1). The sub-cells were manufactured on a common semi-insulating substrate and were isolated by insulating trenches. They were then connected in series by means of a metal interconnection. A dielectric layer prevented short circuits in the active layers.

With this configuration, the MPC output voltage was about 6 V (1 V per sub-cell). This value was sufficiently high to power most electronic circuits, either directly or by means of a direct current (DC)–DC converter.

The device size (active area diameter of 2 mm) was chosen to obtain a trade-off between high efficiency and low coupling losses. The last requirement is usually met with large devices that allow for a higher alignment tolerance during the encapsulation process (see Section 2.2). In contrast, high efficiencies at high-power levels may be obtained using smaller devices [9]. Here, we describe the main details of the MPC manufacture, encapsulation, and characterization.

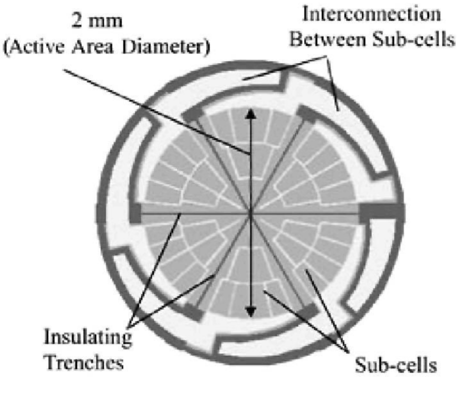

Figure 1. Front view of a multiple photovoltaic converter made up of six series-connected sector-shaped sub-cells. The sub-cells were manufactured on a common substrate and isolated by means of insulating trenches.

2.1. Multiple photovoltaic converter manufacture

Figure 2 shows the semi-conductor layer structure of the manufactured devices. The series interconnections among sub-cells by means of the metal paths are shown.

In contrast to other GaAs PV converters, the structure of the MPC included an etch stop layer under the base to facilitate formation of the isolation trench. A highly doped lateral conduction layer (LCL) was included to decrease the series resistance caused by current circulation beneath the emitter [10].

The MPCs were manufactured according to the process sequence described in [10] with some modifications to improve the device performance at high-power levels.

A busbar interconnection approach was chosen for the series connection between sub-cells. A dielectric barrier was deposited in order to protect the p–n junction from a short circuit.

A spin-on polyimide was used for dielectric barrier implementation. Polyimide facilitated the interconnection between sub-cells because it covered the topographical features on the semi-conductor surface. Therefore, this surface had a fairly uniform aspect, with smooth profiles near the isolation trenches.

A large effort was applied toward reducing the series resistance due to the front contact, metal grid, and interconnections among sub-cells.

To this end, 5-µm wide and 2-µm thick metal fingers were used in the front grid (in place of 3-µm wide and 1-µm thick metal fingers, as are used in conventional MPCs manufactured in our laboratory). The sub-cells were interconnected by metal paths with the same thickness.

Apart from reducing the grid resistance, the increase in finger width also reduced the contact series resistance, which was particularly important in these devices [11].

Series resistance due to lateral current flows was reduced by increasing the thickness of the layers beneath the base (the LCL and the buffer layer). A 4-µm thick LCL and a 2-µm thick buffer were included.

2.2. Multiple photovoltaic converter packaging

The manufactured MPCs were packaged in a housing that incorporated a sub-miniature A (SMA) fiber connector. The assembly provided a device with mechanical and thermal stability, as well as protection from penetration of external agents, such as dust and moisture. The packaging process was as follows.

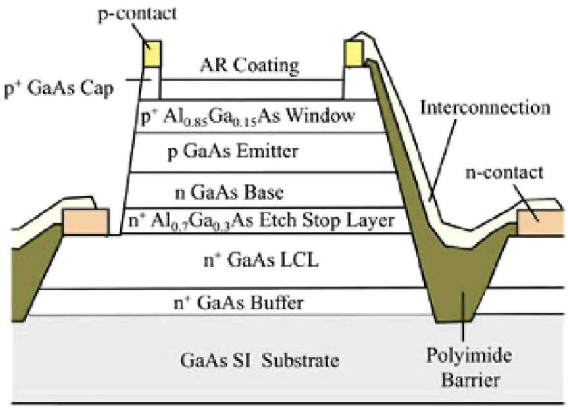

Figure 2. Semi-conductor layer structure of the manufactured multiple photovoltaic converter. The series interconnection between sub-cells by means of metal paths is also shown. AR, antireflection; LCL, lateral conduction layer; SI, semi-insulating.

First, the manufactured MPCs were attached to TO5 packages using a conductive epoxy resin. External wires were bonded to connect the chip to the TO5 pins. For this purpose, an aluminum wedge bonding machine was used. The TO5 packages were attached to aluminum heat sinks designed and manufactured in our laboratory. A thermally conductive epoxy was used to join both pieces. Finally, the heat sink was screwed onto an SMA connector in an aluminum housing.

During the last stage of the process, the MPCs were aligned so that the light that emerged from the SMA connector reached the active area of the device. This process was carried out by monitoring the MPC output power while adjusting the heat sink position relative to the housing. When the maximum power was measured, the whole assembly was fixed using a strong adhesive. This product can endure temperatures in excess of 150 °C, and the housing effectively protected the converter from dust or particle penetration.

2.3. Multiple photovoltaic converter characterization

The packaged MPCs were integrated into the PBL system and were characterized under laser illumination. The maximum of the laser emission spectrum was centered at 808 nm (see Section 3.2).

The MPCs were directly illuminated by the light emerging from the fiber. Under these conditions, both mismatch and coupling losses can cause a significant drop in efficiency relative to that measured under uniform illumination [12]. However, these are the actual conditions under which MPCs are expected to operate in the developed PBL prototype.

The measurement procedure was as follows. The optical power emerging from the fiber was measured using an optical power meter. The MPC was attached to the fiber, and the current–voltage characteristics were recorded.

Figure 3 shows the efficiency measured at different input power levels (P_{in}). The maximum value exceeded 40% at $P_{\mathrm{in}} = 0.5$ W. At $P_{\mathrm{in}} = 1$ W, an efficiency in excess of 38% was obtained, and at $P_{\mathrm{in}} = 3$ W, the efficiency was still higher than 30%, implying an output power as high as 1 W.

Figure 4 shows the open circuit voltage as a function of P_{in}. Voltages exceeding 6.5 V were measured for a P_{in} greater than 0.1 W, and voltages exceeding 7 V were measured for a P_{in} greater than 0.5 W. The maximum V_{OC} measured exceeded 7.1 V.

Figure 5 shows the fill factor as a function of P_{in}. The highest values exceeded 77% at a 0.2 W input power. The fill factor remained well over 70% for P_{in} below 1 W.

3. DEVELOPMENT OF A POWER-BY-LIGHT SYSTEM FOR HIGH-POWER SATELLITE APPLICATIONS

3.1. Background of the application

Figure 6 shows a schematic of the developed PBL system. The system was designed to power a switching regulator that permitted grounding of a PV module in a satellite PV array.

The regulator function was as follows. The power consumption in a satellite changes continuously because of the varying working requirements during a mission. Therefore, the power supplied by a solar array must be regulated to ensure adequate performance during different periods. Because solar arrays are structured into various modules, the power can be managed by switching on/off some of these power assemblies from the main bus.

Each power assembly is controlled by a regulator that can be activated by means of a control signal. When the load current from the main bus is decreased, the regulator is switched, and the corresponding panel stops supplying current. Each panel can be switched on (off) in this way to

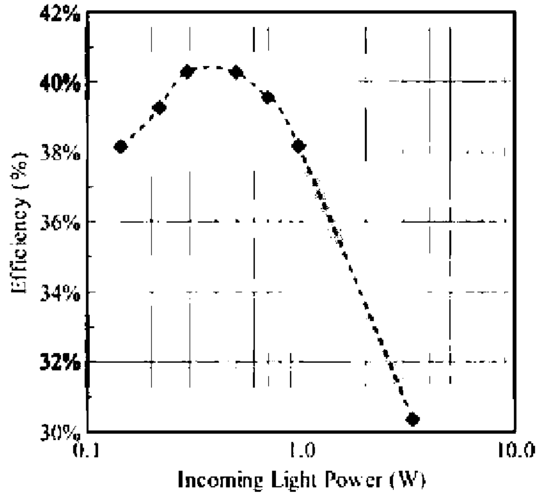

Figure 3. Multiple photovoltaic converter efficiency as a function of incoming light power (P_{in}).

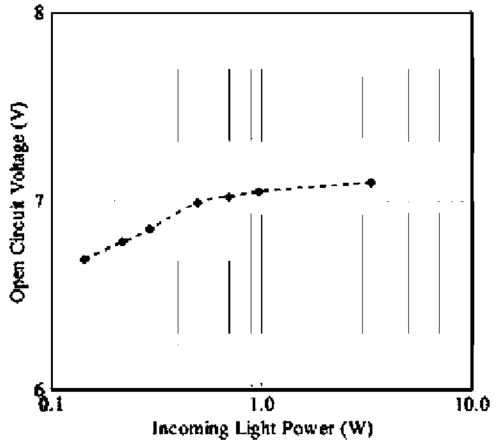

Figure 4. Multiple photovoltaic converter open circuit voltage (V_{OC}) as a function of incoming light power (P_{in}).

adjust the overall output current to the value required at any moment.

The regulator is positioned on the solar panel and must be controlled remotely using cabling of the least possible mass and without creating interference in adjacent electronic devices. Consequently, an optical fiber PBL system is an ideal solution to the problem of controlling these switches. The optical link must provide the required power and withstand the extreme conditions experienced on the exterior of satellites.

As shown in the succeeding paragraphs, the average power consumption of a regulator was 0.2 W, and the input voltage was 10 V. During transients, the maximum input power could be as high as 10 W because the circuit required current peaks of up to 1 A.

The regulator must operate within the temperature range of −70 to +100 °C, as expected on the exterior of a satellite.

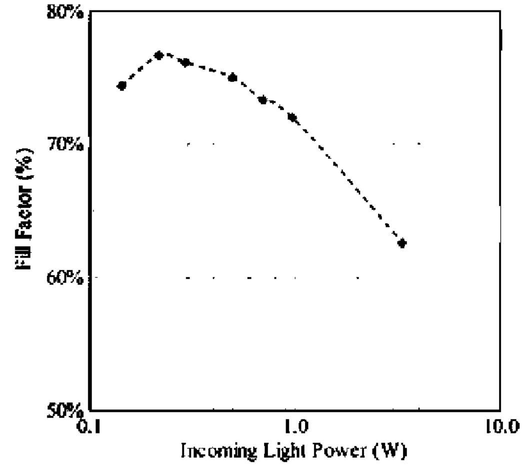

Figure 5. Multiple photovoltaic converter fill factor as a function of incoming light power (P_{in}).

These specifications were considered in the design of the PBL system.

3.2. Power-by-light system description

The developed PBL system consisted of the packaged MPC described previously, a silica optical fiber with SMA connectors at both ends, and a 12-W laser diode. The main features of these components are described in the succeeding paragraphs.

The optical fiber diameter was 400 and 430 μm (core and core with cladding, respectively). The fiber was a step-index multimode fiber with a numerical aperture (*NA*) of 0.37. These features were selected to reduce the coupling losses and are suited to the characteristics of the MPC and the light source.

The fiber length was 8 m, more than sufficient for short-distance applications, such as the PV array control link in a satellite. The attenuation at the laser wavelength was about 8 dB km^{-1}, which is typical for silica fibers at the first optical communication window.

The light source was a fiber-coupled laser diode with an SMA connector. The maximum of the emission spectrum was centered at 808 nm, which was within the range of optimal response for the MPC (Figure 7). The *NA* was 0.34, lower than that of the fiber.

The maximum optical power of the laser was 12 W, more than sufficient for powering the switching regulator. In fact, the optical power required at the fiber input to supply 1 W to the circuit was lower than 4 W. Therefore, the PBL system may be used for other applications that require additional power.

3.3. Power-by-light system characterization

3.3.1. Optoelectronic characteristics.

Table I shows the measured efficiency and losses for the MPC and optical fiber, as well as for the whole system

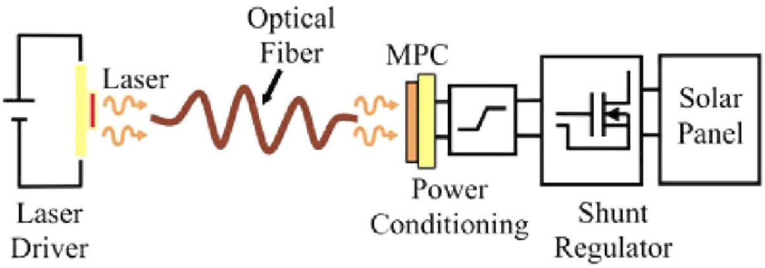

Figure 6. Sketch of the developed power-by-light system. It was made up of a laser diode, an optical fiber, and a multiple photovoltaic converter (MPC). A power conditioning block was used in order to boost the MPC voltage to 10 V and to supply current peaks of up to 1 A to the regulator.

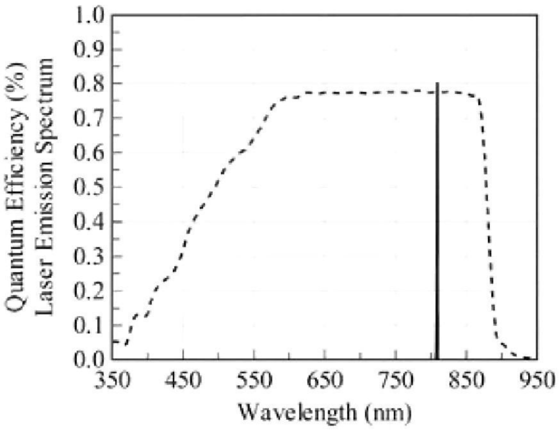

Figure 7. Laser emission spectrum and multiple photovoltaic converter quantum efficiency as a function of wavelength.

(excluding the laser diode), for an output electric power of 1 W. The system efficiency was 27% (including the optical fiber, connectors, and MPC). If the laser diode efficiency is considered, the overall system efficiency was over 10%. The MPC efficiency was 30%, and the fiber link efficiency (including connectors) was 89%. The corresponding losses were 5.7 (system), 5.2 (MPC), and 0.5 dB (fiber link).

The system efficiency was higher for a lower output power because of the higher MPC efficiency. For an output power less than 0.7 W, the system efficiency exceeded 30%. The maximum measured value was as high as 36% at 0.2 W (it is worth noting that this is the average power consumption of the powered circuit, as shown in the succeeding paragraphs). To the best of our knowledge, this value is well over those reported in other published works for similar power levels [2].

Figure 8 shows the current–voltage and power–voltage curves for the MPC at a system maximum power output of 1 W. The MPC output voltages were 5 V at 1 W, 6 V at 0.73 W, and 6.5 V at 0.42 W. For voltages between 2.3 and 6.4 V, the output power (P_{out}) always exceeded 0.5 W. Between 3.3 and 6.1 V, P_{out} exceeded 0.7 W. These values show that the PBL system may power a great variety of electronic circuits either directly or by means of a power conditioning block.

It must be kept in mind that these curves were measured in the actual conditions under which the MPC operates in the PBL prototype. Therefore, the effects of non-uniform illumination can be observed in the current–voltage curve (Figure 8).

Table I. Measured system efficiency (in %) and losses (in dB) for multiple photovoltaic converter (MPC), optical fiber, and the whole system (excluding the laser diode) for an output power of 1 W.

	Efficiency (%)	Losses (dB)
Optical fiber + connectors	89.0	0.5
MPC	30.0	5.2
System	27.0	5.7

3.3.2. Temperature characterization.

It is worth noting that the PBL system maximum power (1 W) was much higher than the maximum consumption of the application (0.44 W; see Section 4). The reason for this is that the powered circuit described in the succeeding paragraphs was intended to operate at temperatures up to 100 °C. Consequently, the system design took into account the decrease in MPC output power as the temperature increased.

The MPC performance was characterized over the temperature range from −70 to +100 °C. The measurements were conducted in a vacuum chamber (Figure 9), which permitted accurate control over the targeted constant or ramped temperature. External wires may be introduced into the system to monitor the desired processing parameters.

The measurement procedure was as follows. The MPC was introduced into the chamber and attached to the end of the fiber. The fiber was connected to the laser diode and placed outside the chamber. The *I*–*V* curve was subsequently monitored.

Measurements began when the chamber temperature reached 100 °C. When both the MPC current and voltage reached a steady state, the *I*–*V* curve was recorded. Subsequently, the chamber temperature was reduced, and the process was repeated at each programmed temperature.

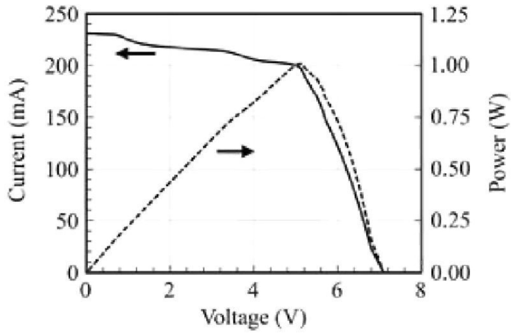

Figure 8. Current–voltage and power–voltage curves for the multiple photovoltaic converter at a system maximum output of 1 W.

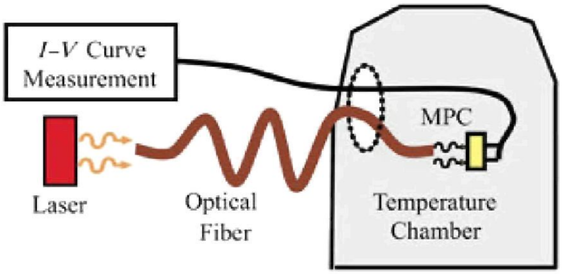

Figure 9. Experimental set-up used for characterizing the multiple photovoltaic converter (MPC) at different temperatures. The devices were put into a chamber, in which the temperature was fixed at the desired value. Then, the MPC was illuminated by means of the optical fiber, and the *I–V* curve was measured.

The MPC output power was found to decrease by about 0.32% per degree Celsius. Consequently, the system output at 100 °C was reduced to 0.76 W, well over the maximum power required by the shunt regulator.

The MPC voltage decreased by 11 mV per degree Celsius. At 100 °C, the voltage was still well over 4 V. This voltage was sufficiently high that it could be boosted by the power conditioning block described in the succeeding paragraphs.

4. OPTICAL POWERING OF A SWITCHING REGULATOR FOR SATELLITE APPLICATIONS

As described, a shunt regulator for controlling the activation and deactivation of the solar panels in satellites was manufactured and optically powered using the PBL system.

The average power consumption of the regulator was 0.2 W, and the input voltage was 10 V. However, during transients, the maximum input power could be as high as 10 W. Therefore, a power conditioning circuit was needed between the MPC and the regulator (Figure 6) to boost the voltage at the circuit input and to supply current peaks of up to 1 A.

A power conditioning block was, therefore, designed and manufactured. The block included a DC–DC converter and an ad hoc peak current controller.

The former was a step-up converter with an adjustable output voltage of up to 12 V, provided that its input voltage was in excess of 2 V. The latter comprised a capacitor and an electronic switch to supply the current peaks.

The power conditioning block and the regulator were successfully powered by the PBL system. During the regulator operation, the MPC output voltage was around 6 V, and the supplied current was close to 40 mA. The power conditioning block boosted the MPC output to 10 V, and during transients, it provided current peaks of up to 1 A. In these periods, the maximum current at the MPC output was 74 mA, whereas the power supplied exceeded 0.44 W. In all cases, the performance of the regulator was satisfactory.

5. CONCLUSIONS

In this work, a PBL system is developed in order to power a shunt regulator for the activation and deactivation of solar panels in a satellite PV array. The work involves the manufacture of a GaAs MPC, a power conditioning block, and a regulator (which were developed ad hoc) and the implementation and characterization of the whole system.

The manufactured MPC was able to supply 1 W at 5 V with an efficiency of 30%. The maximum measured efficiency was over 40% at $P_{in} = 0.5$ W. Open circuit voltage over 7 V was measured for P_{in} over 0.5 W. The maximum V_{OC} measured was over 7.1 V. These values are remarkable for a device with an active area of just 3.1 mm^2.

System efficiency (including optical fiber, connectors, and MPC) of 27% was measured at an output power of 1 W. At $P_{out} = 0.2$ W (this was the average power consumption of the powered circuit), the efficiency was as high as 36%.

The power conditioning block and the regulator were successfully powered with the PBL system. The maximum supplied power in steady state was 0.2 W, whereas in transient state, it reached a value of 0.44 W.

The system was characterized in the temperature range in which it was intended to operate, from −70 to +100 °C. The maximum power delivered at 100 °C was 0.76 W at a voltage well over 4 V. Therefore, the performance of the regulator was ensured in all the temperature range, both in steady and transient states.

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