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55% Efficient High-Power Multijunction Photovoltaic Laser Power Converters for 1070 nm

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Abstract: High-efficiency multijunction laser power converters are demonstrated for the first time at high power for optical inputs around 1070 nm. The InP-based photovoltaic power-converting III–V heterostructures are designed with eight lattice-matched InGaAsP subcells (PT8-1070 nm). Conversion efficiencies of 55% were obtained at 18 W of output power. Endurance testing was performed for over 1000 h of continuous operation with an average output power of 13.2 W at an input wavelength of 1064 nm. An average steady-state efficiency of 54.4% at an ambient temperature of $\sim 20^\circ\text{C}$ was obtained for that duration. The results demonstrate that 1 cm^2 optical power converter devices can produce electrical outputs of 20 W at maximum power voltages around $V_{\text{mpp}} \sim 6\text{ V}$, thus retaining an optimal load near R_{mpp} at $\sim 2\text{ ohms}$. Efficiencies between 57.9% and 59.0% were also obtained for smaller 0.029 cm^2 chips for input intensities between 35 and 69 W/cm^2 . This is an important development for power beaming applications: the unprecedented combination of power and conversion efficiency capabilities is expected to enable deployments for key wavelengths between 1040 and 1080 nm.

Keywords: optical power converters; laser power converters; power-over-fiber; power beaming; photovoltaic; galvanic isolation; InGaAsP; InP; multijunction semiconductor heterostructures



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1. Introduction

High-performance semiconductor optoelectronic devices have advanced continuously in the past few decades. On the emitter side, in the field of high-power lasers, many interesting semiconductor diode solutions are readily available today, covering various wavelength ranges. Furthermore, high-power fiber lasers [1–5], such as ytterbium fiber lasers, are commonly used industrially for applications such as material processing, laser manufacturing for electrification applications, metal welding, and many others. On the receiver side, photovoltaic optical power converters (OPCs) have been developed primarily for the wavelength ranges of 800–850 nm [6–36], 940–990 nm [37,38], and 1450–1550 nm [39–44]. There is also exciting potential for other wavelengths [45–62]. These OPC devices efficiently convert laser light into useable electrical power and are often referred to as laser power converters (LPCs). Many of the initial OPC developments have been focused on wavelengths around 808 nm, benefiting from the availability of laser diodes and the maturity of GaAs-based devices. The 940–990 nm spectral range has also become interesting because of laser diode reliability and cost considerations. The long-wavelength 1450–1550 nm spectral range is predominantly strategic due to its low attenuation in the case of long-distance power-over-fiber applications. Ongoing research related to photovoltaic devices suggests other

potential device developments [63–83], new optical wireless power transmission applications [84–96], new OPC opportunities [97–102], and interesting system design strategies and achievements [103–116].

Nonetheless, it has become clear that high-power fiber lasers represent an interesting prospect for power beaming applications, especially given their unique high quality beam propagation properties. Moreover, most power beaming applications typically require such high-power capabilities. In fiber lasers, the active gain medium is based on optical fiber doped with lanthanide elements (often called rare-earth elements), typically operating around the visible to mid-infrared spectral range. The prevalent ytterbium-doped fiber lasers emit at ~1070 nm, whereas the OPC developments around this wavelength have been limited [50–53,55,60]. No multijunction devices have been developed yet to convert efficient, high-power laser beams around these key wavelengths.

In the current work, we therefore reveal the first commercial multijunction OPCs for the 1040–1080 nm spectral range. The initial results are presented for Broadcom’s new eight-junction InGaAsP/InP concept samples for power beaming applications, called PT8-1070 nm OPCs, intended for operation using high-power 1070 nm laser diodes or fiber lasers.

Relatively large chip areas are necessary for high-power applications; therefore, a new 10 mm × 10 mm product was developed. It is illustrated in Figure 1. The geometry is similar to high-power chips at 808 nm or 975 nm [29,31,32,37,89,90], including two narrow cathode busbars on opposite edges of the front side and a blanket back side metal for the anode. The device details are described in the section below.

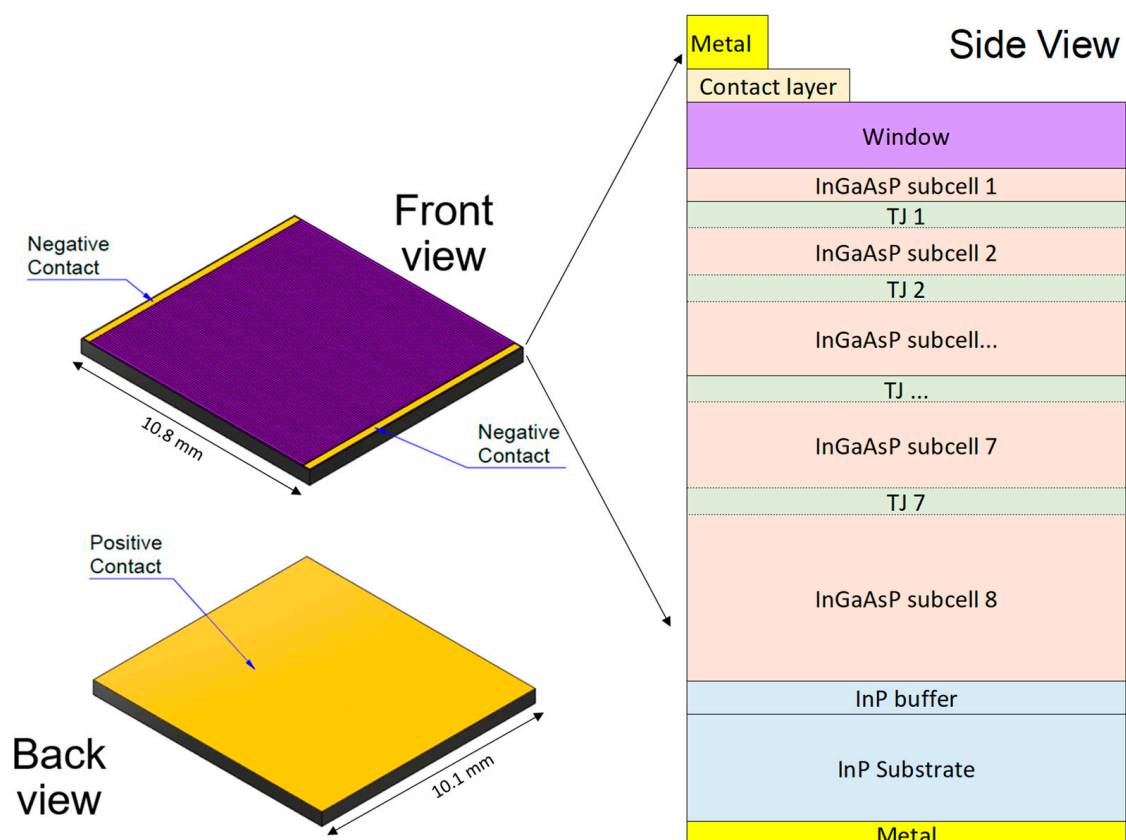


Figure 1. Schematic of Broadcom’s AFBR-POC506A6, a 10 mm × 10 mm PT8-1070 nm Vertical Epitaxial HeteroStructure Architecture (VEHSA design) device prepared with 8 InGaAsP subcells. The right side depicts the cross-section of the heterostructure (not to scale).

2. Materials and Methods

InGaAsP subcells lattice-matched to InP are expected to contribute between ~ 0.85 and ~ 0.9 V of output voltage each, for example, based on previous single junction measurements [70,74]. For the present development, a PT8 design was selected: a vertical multi-junction with eight subcells. This design was selected to achieve an output voltage capable of maintaining an optimal load greater than 1 ohm in operation. The schematic of the $10\text{ mm} \times 10\text{ mm}$ PT8-1070 nm heterostructure is depicted in Figure 1. It is based on the previously described Vertical Epitaxial HeteroStructure Architecture (VEHSA design) [14,15], here adapted for the lattice-matched InGaAsP/InP material system.

The Beer–Lambert law is utilized to determine the required absorber thicknesses of the individual subcells. Each subcell needs to be absorbing $\sim 1/8$ of the incident light. Such a PT8 design is expected to provide output voltages capable of high-power operation. The PT8 arrangement was selected to ensure that sufficient output voltage can be maintained over the industrial temperature range ($-40\text{ }^{\circ}\text{C}$ and $85\text{ }^{\circ}\text{C}$).

For the GaAs-based system, we have previously demonstrated that the output voltage scales linearly up to PT30 devices with 30 subcells [37]. For InP-based InGaAs absorbers, multijunctions with 10 subcells have also been commercialized [42,101,111]. Here, InP-based 8-junction InGaAsP OPCs is the focus of the present study.

The new photovoltaic vertical multijunction structure is built for operation with the optical input from a powerful laser source emitting in a spectral range peaking around 1070 nm. It is designed with eight thin (optically transparent) photovoltaic semiconductor subcells interconnected with tunnel junctions. The tunnel junctions are labelled TJ_i in Figure 1. Each individual subcell comprises an n-type emitter and a p-type base. The key aspects of the design strategy include selecting the absorber material composition such that its bandgap is at a target value with respect to the incident wavelength and then applying the previously described Beer–Lambert formalism to define the thicknesses of each subcells. For this study, we targeted an absorber bandgap between 40 and 50 nm below the incident wavelength. Such a spectral offset should allow satisfactory device performance over the entire operating temperature range of interest. The TJs are made to be as transparent as possible to the input beam, here utilizing InGaAlAsP alloys lattice-matched to InP. The optimization of TJs in InP-based material has been studied previously [14,42,67,79] and is not discussed here.

The epitaxial layers were grown using commercial Aixtron Metal Organic Chemical Vapor Deposition (MOCVD) reactors on 100 mm diameter InP substrates. Common commercial n-type and p-type dopant sources were used, as is customary for industrial devices. The total thickness of all the absorbing emitter and base layers from the different subcells is such that the impinging optical beam is almost completely absorbed. Here, for the InP material system, an InP window is used, and it is transparent to the incident light. An interesting design variation (not used here) consists of reducing the absorber thicknesses of the subcells and using the light reflected from the back side of the device. Indeed, the InP substrate is also transparent to the input light and to the InGaAsP luminescence, therefore allowing the reflected light [27] to be recycled [33–36] from the back side of the device. As described previously [14,15,37], to realize the required photocurrent matching condition, the structure usually has increasing subcell thicknesses from the top subcell (thinnest) toward the bottom subcell (thickest), as illustrated in Figure 1.

The device fabrication included standard blanket back-metallization (Zn-based alloy contacts) [63], front ohmic contacts (such as Pd/Ge/Ti/Pd/Ag/Au or In), and antireflection coatings (ARCs). The ARC is targeted to reduce the reflectivity (R) of the incident beam to $R < 2\%$ for the spectral range of interest.

For testing and characterization purposes, fiber-coupled semiconductor laser diodes were used in this study. It should be expected that testing with fiber lasers would give similar results as long as the beam profile is designed to have a comparable level of uniformity. Moreover, fiber lasers typically have a narrower spectral width compared to laser diodes, but both are relatively narrow compared to the spectral width of the device.

One of the test lasers has a maximum output power of ~ 24.5 W at a wavelength of 1064 nm. It has a numerical aperture of NA ~ 0.22 , using a multi-mode fiber core diameter of 400 μm . Another fiber-coupled laser diode was also used with a maximum output power of ~ 10 W at 1067 nm. It was equipped with an integrated co-linear red aiming beam. The aiming beam is advantageous for obtaining good reproducibility in the alignment of the infrared probe beam with the test samples. For the I–V measurements, the tip of the fiber-coupled laser was positioned to form a circular spot contained within the clear aperture of the sample. The inscribed spot is achieved by positioning the output ferrule at ~ 25 mm above the surface of the sample.

The I–V characteristics were acquired using a Keithley 2601B, Keithley Instruments, Cleveland, OH, USA source-meter for output currents up to 1 amp and with a Keithley 2461 for higher currents. The data were obtained at a temperature of ~ 20 °C. Chip heating was minimized during the bare chip characterization measurements by using short scans, of the order of a few seconds, thereby called the cold-start method. For continuous, long-duration, steady-state measurements, bare chips were mounted on AlN carriers with silver epoxy. The heat extraction from the carriers was further obtained by mounting them on 200 g aluminum heatsinks. A thin layer of thermal interface material with a conductivity of 8.5 W/mK was employed for heat management purposes. An air flow of $> \sim 10$ m³/h was used to maintain the heatsink near the ambient temperature. The output for the device was measured across a fixed power resistor using a data logger from DataQ Instruments, Akron, OH, USA.

3. Results

The results measured with the newly developed 10 mm $\times$ 10 mm PT8-1070 nm are shown in Figures 2–4. Figure 2 shows the steady-state output characteristics of a chip-on-carrier (CoC) sample measured continuously for over 1000 h. As described above, the CoC was prepared by mounting the chip on an AlN carrier with silver epoxy and using an industrial wirebonding process.

Between -100 h and 0 h, various optical input powers were used, progressively stepping up the optical input power from 6 W to 24 W, as indicated in Figure 2. Fixed power resistor loads were used as follows: 11 ohms for a 6 W optical input, 6.8 ohms for a 10 W optical input, 4.4 ohms for a 15 W optical input, 3.36 ohms for a 19.8 W optical input, and 2.75 ohms for a 24.2 W optical input. The loads were selected to correspond to the optimal load (R_{mpp}), as evaluated from the I–V curves of Figure 3 or from the fit derived in Figure 4.

In Figure 2, the test with the fixed optical input power of 24.2 W ran continuously for 1000 h. The input wavelength of 1064 nm was delivered using an ST connector secured with a custom adapter to position the output tip of the fibered laser approximately 24 mm above the center of the sample. The OPC's output power (measured across the 2.75-ohm power resistor) is indicated on the left vertical axis (black curve), and the corresponding conversion efficiency is shown on the right vertical axis (blue curve). Clearly, the output is stable over time. No observable performance degradation was observed for the 1000 h duration. The small fluctuations in the output power are attributable to minor drifts in the ambient temperature during the days of the ~ 6 -week period.

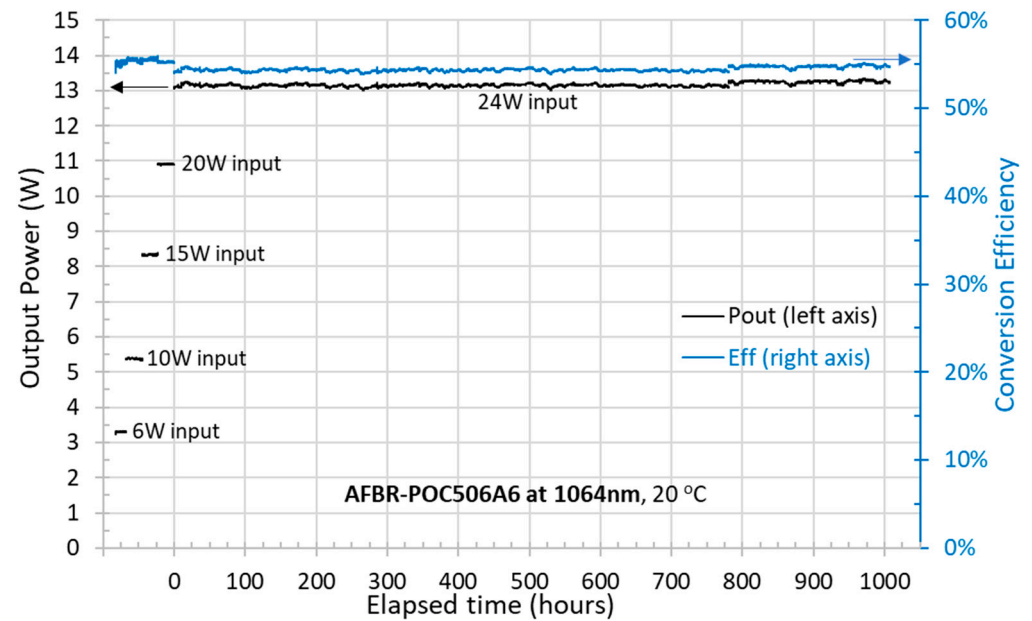


Figure 2. Steady-state output characteristics of the 10 mm × 10 mm PT8-1070 nm measured for over 1000 h. Various optical input powers (as indicated) were used between −100 h and 0 h, and a fixed optical input power of 24 W was maintained for the following 1000 h. The input wavelength is 1064 nm, the output power measured across a 2.75-ohm power resistor (from 0 to 1000 h) is indicated on the left vertical axis (black curve), and the corresponding conversion efficiency is shown on the right vertical axis (blue curve).

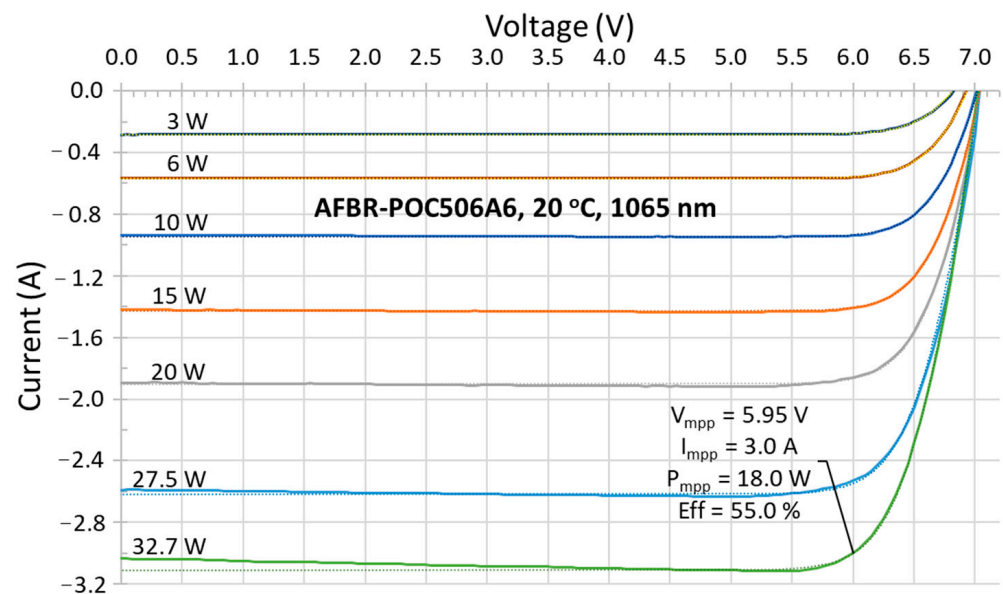


Figure 3. Measured I-V properties (solid curves) at 20 °C for a 10 mm × 10 mm PT8-1070 nm OPC operating with laser power peaking between 1064 nm and 1067 nm for input powers between 3 W (upper dark-blue curve) and 32.7 W (lower green curve). At 32.7 W of input power, and efficiency of $Eff = 55.0\%$ is obtained with a V_{oc} of 7.02 V. The output power (P_{mpp}) reaches 18 W with $V_{mpp} = 5.95$ V and $I_{mpp} = 3.0$ A. The diode equation fit (model) to the illuminated I-V curves is also shown with the overlapping dotted curves for each optical input power.

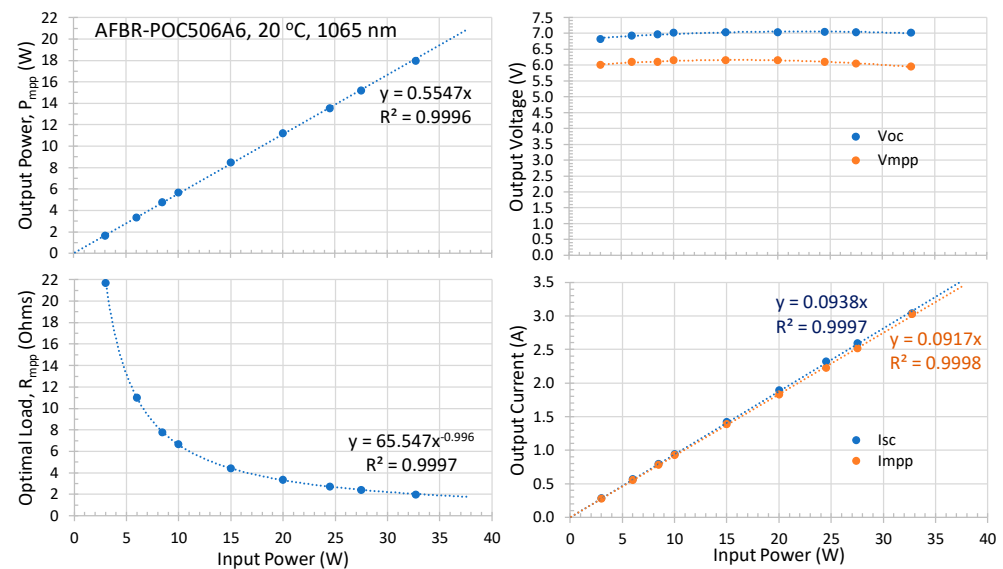


Figure 4. The optical input power dependence of a 10 mm × 10 mm PT8-1070 nm OPC operating at 20 °C with laser power peaking between 1064 nm and 1067 nm. The electrical output power, P_{mpp} , is shown in the top-left; the output voltage, open-circuit voltage (V_{oc}), and maximum power point voltage (V_{mpp}) are shown in the top-right; the optimal load, R_{mpp} , is shown in the bottom-left, and the output current, short-circuit current (I_{sc}), and maximum power point current (I_{mpp}) are shown in the bottom-right. The values of the corresponding regressions are indicated in the plots.

Figure 3 shows the measured I–V curves for various optical input powers between $P_{in} = 3$ W and $P_{in} = 32.7$ W. At 32.7 W of laser power, an efficiency of $Eff = 55.0\%$ is obtained with a V_{oc} of 7.02 V. The output power (P_{mpp}) reaches 18 W with $V_{mpp} = 5.95$ V and $I_{mpp} = 3.0$ A. Diode equation fits, based on a previously described model [76], are also shown together with the measured illuminated I–V curves: the overlapping dotted curves in Figure 3. As can be deduced from Figure 3, closely correlated fits are obtained. The fit is based on an 8J ideal diode equation with all the subcells having an ideality factor of $n = 1.038$. An overall series resistance of 0.12 ohm is extracted for the 15 W curve.

It is foreseen that these OPCs can operate at higher optical powers, but due to the limited laser power available in our setup, the experimental scope of the present study is restricted to optical input powers below 33 W.

The important characteristics of the I–V curves of Figure 3 are analyzed in more detail in Figure 4. The input power dependence of key parameters is plotted. The top-left plot of Figure 4 shows that the output power P_{mpp} has a measured slope efficiency of $Eff \sim 55.5\%$ with negligible deviations from a linear regression for optical input powers up to 33 W.

As mentioned above, the input power was limited by the maximum laser power available. The two lasers described above had to be used simultaneously to reach ~ 33 W via the dual beam method [29]. Provided adequate heatsinking is available for the device, we expect it would be possible to use higher optical input powers without damaging the photovoltaic laser power converter. In the high power range, it is also important to fill the chip aperture as much as possible in order to distribute the heat load and to avoid spiky optical and heat profiles.

The output voltage is shown in the top-right panel of Figure 4. The open-circuit voltage (V_{oc}) reaches a maximum value of 7.040 V, while the maximum power point voltage (V_{mpp}) is then 6.15 V. It corresponds to an average voltage of 0.880 V per subcell, yielding a bandgap voltage offset value of $W_{oc} \sim 0.234$ V, where $W_{oc} = (E_g/q) - V_{oc}$, with E_g being the bandgap energy (here InGaAsP lattice-matched to InP) and q the electronic charge.

The optimal load R_{mpp} is shown in the bottom-left panel of Figure 4. The corresponding fit is derived from the measured data and provides the necessary load information for fixed load measurements at various optical input powers, as in Figure 2.

The output current is shown in the bottom-right panel of Figure 4. The short-circuit current (I_{sc}) yields a responsivity of 93.8 mA/W. Taking into account the eight junctions of the PT8, for a wavelength of ~ 1065 nm, this corresponds to an $EQE_{I_{sc}}$ of 87.4% (the external quantum efficiency measured at the short-circuit current point). The maximum power point current (I_{mpp}) is measured to have a responsivity of 91.7 mA/W, corresponding to an EQE_{mpp} of 85.4% (the external quantum efficiency measured at the maximum power point).

Figure 5 shows the *Optimal Load Chart* obtained with several previously characterized OPC designs. The plot is updated with the new 10 mm $\times$ 10 mm PT8-1070 nm OPC results from two samples from the present study (open and solid green triangles). It shows the measured optimal load ($R_{mpp} = V_{mpp}/I_{mpp}$) as a function of the electrical output power ($P_{mpp} = V_{mpp} \times I_{mpp}$), and it further demonstrates that multijunction OPCs uniquely allow efficient high-power conversion for various wavelengths of operation [37].

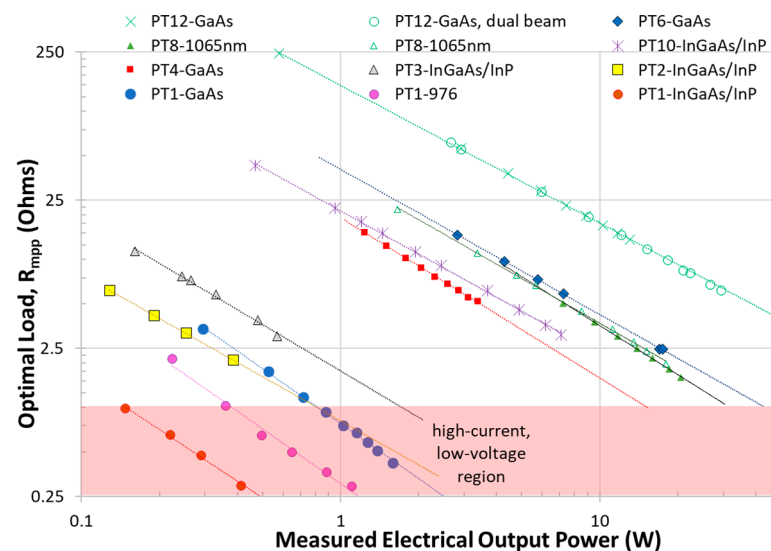


Figure 5. The measured optimal load ($R_{mpp} = V_{mpp}/I_{mpp}$) as a function of the output power obtained with various OPC designs, demonstrating that multijunction OPCs allow efficient high-power conversion for various wavelengths of operation. This *Optimal Load Chart* is updated with the 10 mm $\times$ 10 mm PT8-1070 nm OPC results from two samples (open and solid green triangles). The lines are the corresponding regressions. Updated from Fafard, S. and Masson, D.P. *Photonics* **2022**, *9*, 438. Copyright 2022 Author(s), licensed under a Creative Commons Attribution (CC BY) license [37].

Based on the high-performance of the OPCs, as evident from Figures 2–5, Broadcom is now in the process of commercializing the 10 mm $\times$ 10 mm PT8-1070 nm design under the product name AFBR-POC506A6. To that effect, Figure 6 shows histograms for a pilot manufacturing lot of concept samples. The test results were obtained with bare chip probing with a 3 W optical input at 1067 nm. For such bare chip probing, the back side of the chip is in electrical contact with a metal chuck, and four-wire needle probing is performed between the front busbars and the back side. This procedure keeps the chips in pristine shape for future uses, and the direct mechanical thermal interface for such chip-on-chuck testing is typically sufficient for 3 W optical probing using the cold-start approach described above. Key relevant statistics are shown in Figure 6 for 139 known-good-die chips tested with the chuck set at 20 °C.

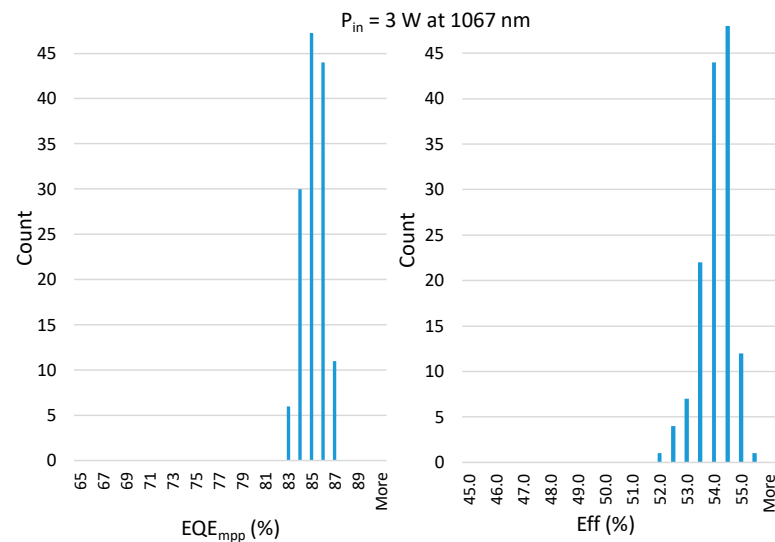


Figure 6. Histograms for a manufacturing lot of concept samples of Broadcom's AFBR-POC506A6 PT8-1070 nm OPCs, for 10 mm × 10 mm chips at 20 °C. The external quantum efficiency at the maximum power point, EQE_{mpp} , is shown on the left, and the conversion efficiency is shown on the right for bare chip probing with a 3 W optical input at 1067 nm.

The histogram for the external quantum efficiency based on the maximum point current (I_{mpp}) is shown on the left of Figure 6: EQE_{mpp} . A tight distribution is obtained with a mean EQE_{mpp} of 84.7% and a standard deviation of 1.0%abs.

The conversion efficiency ($Eff = P_{mpp}/P_{in}$) is shown on the right of Figure 6. A mean efficiency of $Eff = 53.8\%$ is obtained with a standard deviation of 0.6%abs. The above testing was performed at a low irradiance of 3 W/cm². The efficiency will further increase for operations at higher input power on mounted chips.

To operate at higher powers, the chips must be mounted on carriers, for example, as was the case for Figures 2–5. The maximum irradiance in Figures 3 and 5 was 33 W/cm².

To measure the performance at higher irradiance, smaller chips can also be evaluated. To that effect, the wafer layout also incorporated 0.029 cm² test chips. Figure 7 shows the optical input irradiance dependence of the conversion efficiency, up to ~70 W/cm². Four 0.029 cm² PT8-1070 nm OPCs from the same pilot batch are shown. At a 20 °C, with an optical input wavelength of 1067 nm, efficiencies between 57.9% and 59.0% are obtained for input intensities between 35 and 69 W/cm².

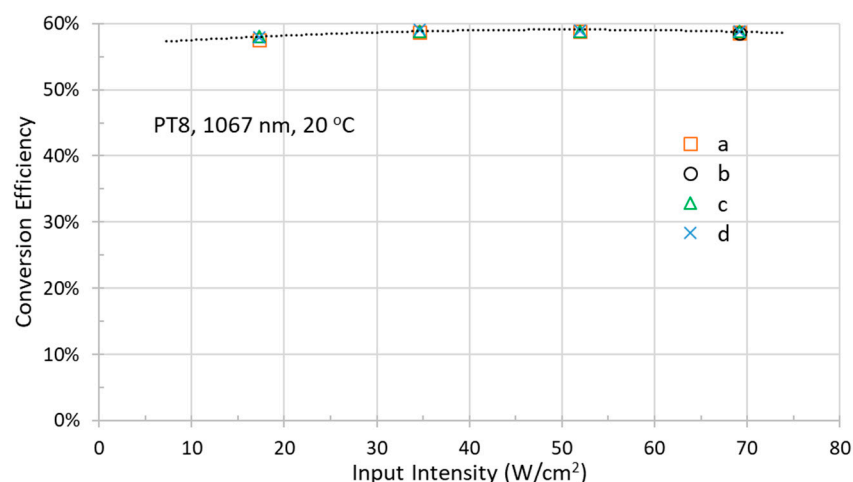


Figure 7. The optical input irradiance dependence of the conversion efficiency for 0.029 cm² PT8-1070 nm OPCs at 1067 nm at 20 °C. The results for samples a, b, c, and d are shown.

It is interesting to note that in the solar field, $100 \times \text{AM1.5}$, commonly called 100 suns, corresponds roughly to 10 W/cm^2 , whereas the present study covered average irradiance up to 33 W/cm^2 for the 10 mm chips and up to almost 70 W/cm^2 for the smaller chips. It would therefore roughly correspond to an irradiance between the solar equivalent of 330 and 700 suns. The results reveal that the laser light can be concentrated at least to such levels as long as the thermal management is sufficient. The more concentrated irradiance in Figure 7 produced higher conversion efficiencies, mainly because of the higher output voltage obtained under these conditions.

4. Discussion

Laser power beaming applications at high power require large area photovoltaic devices designed to produce high output voltages and therefore support large currents with minimal resistive losses. The InP-based lattice-matched 8J heterostructure design, with the 1 cm^2 form-factor of Figure 1, allows single units to be built that are expected to support up to 20 W of usable electrical power. The chips can also be arranged in arrays to scale up the output power.

In most practical cases, it is often advantageous to operate the laser power converter devices in an under-filled illumination mode [29]. For example, the laser beam typically has a round geometry and a relatively spiky profile; therefore, partial illumination is normally unavoidable. The results of Figure 2 demonstrate that the newly developed PT8-1070 nm can operate under these conditions with stable efficient output for 1000 h without observable performance degradations. We demonstrated continuous operation with 13.2 W of output power averaged over 1000 h with a mean conversion efficiency of 54.4% measured through a load of 2.75 ohms. Such an unprecedented combination of power capability and conversion efficiency is expected to enable the deployment of power beaming solutions in the 1040–1080 nm spectral range.

This study also demonstrated 18 W electrical output power at 55% conversion efficiency in Figures 3–5. To reach output power of over 20 W, it is important to engineer the thermal management strategy adequately to avoid excess heating. For example, sufficient spatially concentrated currents can lead to sudden runaway conditions. Therefore, high thermal conduction in the chip assembly process is critical to avoid chip damage within a concentrated beam operation. It should be expected that this consideration is particularly relevant for the case of high-power fiber lasers, which often have a spikier Gaussian beam profile.

This study exemplified the use of silver epoxy for the assembly process on AlN carriers. The new PT8-1070 nm OPC chips would also be compatible with a solder assembly process, but in either case, it also is important that the assembly process does not leave voids under the chips.

Figure 4 demonstrates a linear output power with input power over the range studied. The relation of the optimal load with the input power was derived. An operational output voltage of ~6 V was revealed. An EQE_{mpp} of 85.4% was obtained at 1065 nm.

Figure 5 demonstrates that new PT8-1070 nm OPCs have an optimal load characteristic comparable to GaAs-based PT6 but also feature the advantage of efficient operation at strategic wavelengths around 1070 nm. Overall, this makes these OPC devices suitable for operations at high input powers for key wavelengths for power beaming applications.

5. Conclusions

In conclusion, the high-efficiency capabilities of multijunction laser power converters were demonstrated at high power for an optical input around 1070 nm. The vertical multijunction VEHS strategy has once again been proven very effective at trading photocurrent

in favor of increasing the operating voltage for a new spectral range: an important development for power beaming applications. Conversion efficiencies of $\text{Eff} \sim 55\%$ were measured at electrical outputs 18 W for an input wavelength of ~ 1065 nm. These new lattice-matched InP-based PT8-1070 nm devices are giving a V_{mpp} of 5.95 V and an EQE_{mpp} of 85.4%, as measured for a pilot lot of concept samples.

Endurance testing was performed for over 1000 h of continuous operation with an average output power of 13.2 W at an input wavelength of 1064 nm, giving an average steady-state efficiency of 54.4%. Efficiencies between 57.9% and 59.0% were demonstrated for smaller 0.029 cm^2 chips for input intensities between 35 and 69 W/cm^2 .

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Conflicts of Interest: The authors declare no particular conflicts of interest, but it should be noted that the authors are employed by Broadcom, a company that manufactures and sells semiconductor components, including power converter devices.

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