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[OWPT-3-04] Non-Uniform Illumination Impacts on O-Band InGaAsP and Metamorphic GaInAs Photonic Power Converters

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Single-junction photonic power converters designed for operation in the telecommunications O-band are measured under 1319-nm laser illumination with a range of beam diameters. Device performance is found to improve as the illumination becomes more uniform. Two absorber materials are evaluated in this study, InGaAsP lattice-matched to InP and metamorphic GaInAs on lattice-mismatched GaAs with maximum efficiencies of nearly 53% and 49% respectively.

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Non-Uniform Illumination Impacts on O-Band InGaAsP and Metamorphic GaInAs Photonic Power Converters

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***Abstract**: Single-junction photonic power converters designed for operation in the telecommunications O-band are measured under 1319-nm laser illumination with a range of beam diameters. Device performance is found to improve with increasing beam size as the illumination becomes more uniform. Two absorber materials are evaluated in this study, InGaAsP lattice-matched to InP and metamorphic GaInAs on lattice-mismatched GaAs with maximum efficiencies of 52.9% and 48.8% respectively.*

1. Introduction

Photonic power converters (PPCs), which convert light into electricity through the photovoltaic effect, are crucial components in photonic power systems. The optical-to-electrical conversion efficiency of these devices is essential to the performance of complete power-by-light systems. Very high efficiencies up to 66% have been achieved for GaAs-based PPCs [1], operating in the 800–850-nm band. Efficiencies up to 51% have been achieved for PPCs operating in the O-band around 1310 nm [2].

An important limiting factor in PPC efficiency is related to non-uniform illumination from laser beams with intensity cross-sections that are typically Gaussian in shape. This leads to non-uniform current generation, ohmic losses and reduced output voltage due to lateral current flow and localized heating.

In this work, we study the impact of non-uniform illumination on the performance of PPCs designed and fabricated at Fraunhofer ISE for O-band operation [2]. Current-voltage (*I-V*) characteristics are measured for two designs under 1319-nm illumination with beam diameters ranging from 1.2 to 2.3 mm.

2. Materials and methods

Two absorber materials targeting O-band absorption are investigated in this study, namely InGaAsP lattice-matched to InP and lattice-mismatched GaInAs grown on a GaAs based engineered substrate [2]. The latter uses a GaInP-based step-graded metamorphic (MM) buffer to overcome the lattice mismatch [3]. A tunnel junction connects the buffer layers of the MM-GaInAs PPC with the PPC layers. The PPCs have active areas of 2.2×2.2 mm² (between the busbars), the nominal designated areas are 0.054 cm². Further fabrication details are given in Ref. 2.

I-V characteristics were measured on a temperature-controlled chuck at 25°C under laser illumination centered at 1319 ± 2 nm with a linewidth of ~9 nm. The collimated output of the fiber-coupled laser was passed through a converging lens directly above the PPC. The circular spot size was controlled by adjusting the lens-to-sample distance and measured using the knife-edge technique. The incident power *P* was determined using a photodiode detector. Profiles for two spot sizes are shown in Fig. 1a and b. The data was fit assuming a super-Gaussian intensity profile

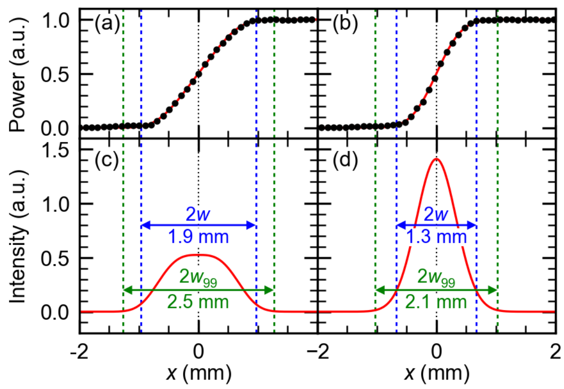

Fig. 1. (a), (b) Knife-edge beam profile measurements with the curve-fit shown in red for two spot sizes. (c), (d) Super-Gaussian beam-shape extracted from the fits. The $1/e^2$ diameter ($2w$) and the diameter containing 99% of the power ($2w_{99}$) are labelled. The beam profiles are normalized to a total power of 1.

$$I(x) = I_{\mathrm{peak}} e^{-2\left|\frac{x}{w}\right|^{\beta}} \tag{1}$$

where x is the position relative to the center of the beam, I_{peak} is the peak intensity, β is the shape parameter, and w is the $1/e^2$ radius. Corresponding super-Gaussian profiles for two spot sizes are shown in Fig. 1c and d.

For comparison purposes, beam uniformity is quantified using the peak-to-average ratio (*PAR*), given by

$$PAR = \frac{I_{\mathrm{peak}}}{I_{\mathrm{avg}}} = \frac{I_{\mathrm{peak}}}{0.99P/(\pi w_{99}^2)} \tag{2}$$

where I_{avg} is the average intensity, P is the total incident power, and w_{99} is the radius that contains 99% of the incident power. The beam parameters for all of the spot sizes used for this study are given in Table 1.

3. Results and discussion

The *I-V* characteristics for both PPC samples are shown in

Table 1. Laser beam parameters

$2w$ (mm)	β	$2w_{99}$ (mm)	*PAR*
2.3	3.40	2.9	2.47
1.9	3.11	2.5	2.68
1.7	2.95	2.2	2.82
1.3	1.98	2.1	4.72
1.2	1.64	2.0	6.64

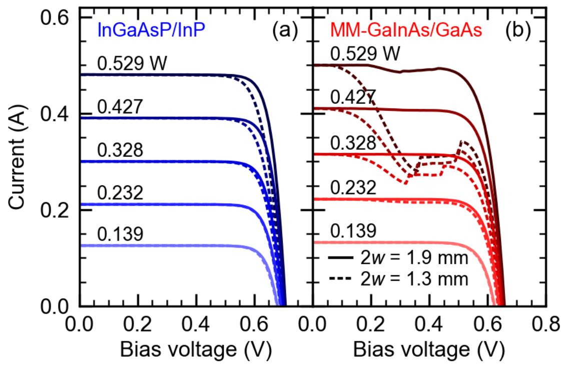

Fig. 2. *I-V* curves at incident powers *P* ranging from 0.139 to 0.529 W for (a) InGaAsP and (b) MM-GaInAs PPCs. The solid and dashed lines indicate $1/e^2$ spot diameters of 1.9 and 1.3 mm.

Fig. 2 for a range of incident powers and $1/e^2$ spot diameters ($2w$) of 1.9 and 1.3 mm.

For the InGaAsP PPC, the fill-factor is smaller for the less uniform illumination profile ($2w$ = 1.3 mm), an effect that becomes more pronounced as the incident power increases up to 0.529 W. We attribute the reduced fill-factor to resistive losses and localized heating in the PPC.

For the MM-GaInAs PPC, the differences in the *I-V* curves for the two spot sizes are more impactful. As I_{peak} increases, there is a corresponding increase in the local current density at the center of the laser spot. When the local current density exceeds the maximum tunneling current density of the embedded tunnel junction, its transport mechanism evolves from tunneling to thermal diffusion, which has much higher resistance. This causes an abrupt drop in the total current [4].

Under the measurement conditions, responsivities of 0.912 A/W and 0.957 A/W were found for the InGaAsP and MM-GaInAs PPCs respectively. The open-circuit voltage (V_{OC}) and short-circuit current were fit to the non-ideal diode equation up to 0.14 W. Ideality factors of 1.01 and 1.32 were obtained for InGaAsP and MM-GaInAs PPCs with corresponding dark saturation currents of 1.01×10^{-12} and 1.39×10^{-9} A. At higher incident powers, non-uniform illumination effects grew in significance, resulting in higher resistive losses and localized heating. Similar fitting parameters were found for all spot sizes.

The bandgap-voltage offset $W_{\text{OC}} = E_g - V_{\text{OC}}$ is plotted against the incident power in Fig. 3a with corresponding fits to the non-ideal diode equation. Deviation from the trends is observed for incident powers above 0.1 W and is more pronounced for the smaller spot diameters.

The measured efficiency is plotted as a function incident power in Fig. 3b. The maximum efficiency for the InGaAsP PPC of 52.9% is measured at P = 0.353 W and $2w$ = 2.3 mm. The roll-off in efficiency becomes more pronounced as $2w$ decreases and the beam becomes less uniform. For the MM-GaInAs on GaAs PPC, the maximum efficiency is 48.8%, measured at P = 0.413 W and $2w$ = 2.3 mm. The roll-off at smaller spot sizes is even more pronounced due to the tunnel junction effects depicted in Fig. 2b.

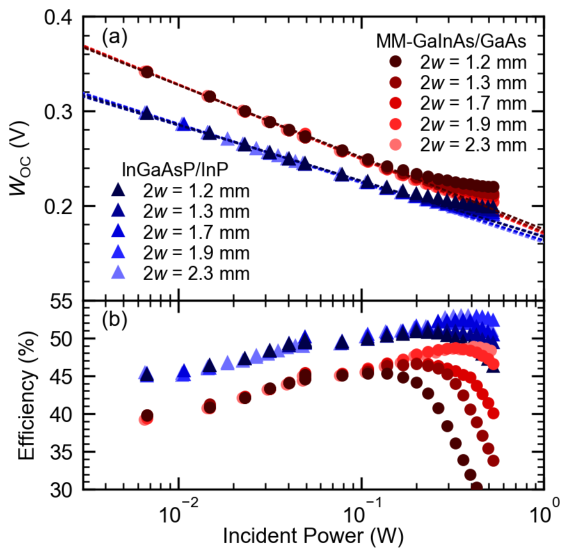

Fig. 3. (a) W_{OC} and (b) efficiency as a function of incident power for $1/e^2$ spot diameters between 1.2 and 2.3 mm. Fits to the non-ideal diode equation are shown in (a) as dashed lines.

8. Conclusion

Single-junction photonic power converters designed for O-band operation were measured under non-uniform laser illumination. Very high efficiencies up to 52.9% for InGaAsP on InP and 48.8% for MM-GaInAs on GaAs were achieved at input powers of 0.353 W and 0.413 W, respectively. The impact of non-uniform illumination on the voltage becomes apparent above 0.1 W, as the W_{OC} deviates from the trend observed at lower powers. The magnitude of deviation is smallest for the larger spot sizes for which the illumination is most uniform. In general, for high incident powers where resistive losses matter, the performance is found to improve with increasing spot size, and thereby lower peak current density, for both devices. Improved performance can be obtained by engineering more uniform illumination profiles across the active device area.

Acknowledgment

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