Multijunction photovoltaic converters for information and power transmission systems

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Abstract. Characteristics of heterostructure PV converters under ultra-high high power frequency modulated laser beams have been modeled and investigated. Dynamic properties of GaAs based multijunction cells have been studied, and estimations of efficiencies for such devices were carried out. It has been established that high efficiency values for conversion of modulated radiation can be obtained only at a minor depth of modulation (±3–3.5 % of the average power). And for converters comprising 3-6-junction, limitations for the acceptable modulation depth are stricter. The achievable bandwidth exceeds 300 MHz at modulation “up” with respect to the maximum power point, and at modulation “down” is more than 500 MHz in the range of laser power of 30-45 dBm. The number of subcells in the multijunction structure does not affect the limiting indicators of fast operation and efficiency, but shifts the point of their achievement towards the higher laser radiation powers. It has been shown that the influence of the photocurrent mismatch among photoactive subcells results in deterioration of both efficiency and fast operation parameters. So, at the mismatch of 5 %, the bandwidth appears to be lower by about 6 % compared to single-junction converters operating under modulated laser radiation, and the efficiency – by 1.5 % correspondingly.

1. Introduction

Systems for power transmitting by a laser beam allow avoiding appearance of transient electromagnetic radiations and interferences, and themselves are resistant to them. Besides, they allow realizing an ideal galvanic isolation between a source and a receiver. Also they can be used for both wireless power transmission and in systems for power-over-fiber supply [1].

The highest efficiency in such systems is ensured by a combination of AlGaAs/GaAs lasers and PV converters based on GaAs [2-6]. A traditional approach is spatial or spectral separation of power and information transmission channels [1]. However, there exists an alternative of transmitting powerful laser radiation (LR) modulated initially by a high frequency, which ensures transfer of both power and information signal via one transmitter, receiver and media [7, 8]. For this reason, of interest are modulated laser power converters (MLPCs).

It has been shown in [8] that the information transfer rates for MLPCs limited by receiving devise noise exceed 1 Tbit/s if a complex law of modulation is employed. At a simple two-level law, rates of 400 Mbit/s are practically achievable. In this case the LR conversion efficiency can be at a level of 50–55 %.

Increasing the number of series connected PV subcells allows raising operation voltage and lowering operation current at the same output electric power [6]. Also a rise of AC signal amplitude, carrying information, is achieved, what improves its reliability and detection quality. In the present work, a task to study the effect of modulation modes on the bandwidth and efficiency of MLPC of multijunction (MJ) configuration was posed.
2. Investigated structures and simulation method

To investigate peculiarities of high-power conversion by MJ MLPCs based on the n-p GaAs structure with InGaP window layer that similar to those studied in [8] were simulated. Schematic of their epitaxial structure is presented in figure 1. The bottom GaAs subcell of a MJ MLPC repeated the structure of a single-junction PV converter. In the row of top GaAs subcells the layers were thinner to reduce radiation absorption and to ensure photocurrent matching among p-n junctions.

The MLPC current-voltage characteristics were formed with using three-dimensional distributed equivalent circuit with the total number of units of 500. That ensured allowing for current spreading along the lateral direction and for nonlinearity of resistive losses in the internal layers, under the contact grid and also in the contacts themselves [9]. Separate units of the subcells were described by a two-diode circuit including the injection and recombination mechanisms of a current flow through a p-n junction.

The densities of dark currents and photocurrent were calculated on the basis of symbolic solution of the diffusion-drift problem in the photoactive layers. The photoresponse external quantum yield of a MPLC for the 809 nm wavelength of laser radiation was about 90 % including the contact grid shadowing. Calculated densities of the injection ($I_{inj} = 8 \cdot 10^{-21} \text{A/cm}^2$) and recombination ($I_{rec} = 6 \cdot 10^{-11} \text{A/cm}^2$) currents fitted well to the experimental values for similar structures grown by the MOVPE technique in the Ioffe Institute. The dark current densities of the top subcells were somewhat lower owing to thinner photoactive layers, but they were of the same order.

Size of the MLPCs under study has been chosen to be equal to 3x3 mm as ensuring acceptable heat removal and absence of effects of high level of excitation in converting LR of up to 45 dBm power. The contact grid had a two-dimensional pattern optimized for the window thickness of 450 nm and LR power of 35 dBm in the case of a single-junction MLPC. The width of its fingers was 5 µm at the pitch of 100 µm and the thickness of 2 µm.

The MLPC bandwidth in the photovoltaic mode is determined by the time constant of separating nonequilibrium charge carries $\tau_0$ and by the p-n junction diffusion capacitance $C_{pm}$ in the operating mode:

$$\Delta f = \left[ \frac{1}{\tau_0 + 2 \pi \cdot R \cdot C_{pm}} \right]^{-1}, \quad (1)$$

The diffusion capacitance was calculated by solving drift-diffusion equations for the considered p-n junction [8]. The charge carrier separation time constant was calculated according to [10] and had an order of $10^{-11}$ s, so can be neglected for the studied cells.
3. Results and discussion

The main characteristics of a MLPC from the point of view of power conversion and information signal transmission are: the efficiency and the bandwidth and also the AC voltage amplitude.

Investigated were the characteristics of a MLPC with the different number of photoactive GaAs p-n junctions. Figure 2 presents the simulation results of the enumerated above parameters in dependence on the 30 dBm LR modulation depth. It was supposed at calculations that the information signal is coded with the equal amount of zeros and ones.

![Figure 2](image_url)

**Figure 2.** Specific AC voltage (a), bandwidth (b) and PV efficiency (c) of the simulated MLPCs at 30 dBm laser 809 nm radiation.

From the plot of the AC voltage amplitude normalized to the number of photoactive p-n junctions (see figure 2a), it is clear that a shape of the information signal being detected does not depend on the number of subcells. The AC voltage value differs substantially for different modulation modes:

- the modulation mode “down” corresponds to the MLPC voltage reduction with respect to the maximum power point in transmitting an information signal and ensures a sharper increase in the amplitude of the AC voltage;
- the modulation mode “up” corresponds to the the MLPC voltage rise with respect to the maximum power in transmitting an information signal and is characterized by a more smooth dependence.

The bandwidth, in this case, for the modulation “down” is, practically, constant, and for the modulation “up” it narrows. For the efficiency, the reverse dependence is typical – the efficiency drop occurs rather slowly with increasing the modulation depth in the direction “up” and, as to the direction “down”, the efficiency value drops drastically after certain modulation value. This boundary of the drop is associated with a point on the I-V characteristic, when the voltage amplitude comes to zero in the mode of stabilization of current preset by a choke \( L_{DC} \) (see figure 1c). With increasing the number of subcells, the bandwidth narrows and the efficiency decreases. This is associated with the decrease of p-n junction current densities deteriorating both thermodynamic conditions for LR conversion and the time constant due to the rise of \( R_C \) for a given LR power. Thus, the modulation mode “down” is more preferential for MLPCs.

In case of conversion of modulated LR by a MJ MLPC, an important is the photocurrent matching for subcells. Due to deviation of layers’ physical parameters at fabrication of PV converters, it is impossible to create an ideally matched structure. As a convenient criterion for estimating a mismatch, one can accept the following coefficient:
where $I_{ph}^{\text{max}}, I_{ph}^{\text{min}}$ – maximum and minimum photocurrents of MJ MLPC subcells.

To investigate the effect of the photocurrent mismatch on the MLPC characteristics, the latter were modeled in the dependence on the value $\xi$ for 2 and 6 p-n junction cells (figure 3). It is seen that the general shape of the dependencies is conserved (see figure 2). However, the mismatch increase leads to narrowing of the bandwidth and deterioration of the efficiency. In the “down” mode, the modulation depth is essentially limited, what results in the intermittent drop of the LR conversion efficiency. It should be noted that the useful voltage amplitude for both structures at a mismatch of 10% does not exceed 50 mV.

![Figure 3](https://example.com/figure3.png)

*Figure 3.* Influence of the MJ subcell photocurrent mismatch on characteristics of the double-junction (a-c) and 6-junction (d-f) GaAs LPC at 30 dBm 809 nm laser radiation. Subcell photocurrent mismatch: 1 – no mismatch, 2 – $\xi = 2\%$, 3 – $\xi = 5\%$, 4 – $\xi = 10\%$.

Dependencies of the MLPCs parameters on the LR power are depicted in figures 4 and 5. At the absence of a photocurrent mismatch for subcells, the modulation mode “down” ensures in 2–5 times higher amplitude of an information signal. The maximum bandwidth is achieved at the same power as the maximum efficiency does. It widens from 450 to 550 MHz with the number of photoactive p-n junctions and at greater incident radiation power. The efficiency or 2-3-junction MLPCs is higher than that of single-junction ones. However, further increasing the number of photoactive subcells results in its drop. This is explained by that losses in the tunnel diodes, in this case, overcome the profit from the reduction of the resistive losses in the contact grid.

In the case of the mode “up” for modulation, the picture changes a little bit. The maximum bandwidth for the modulation depth of 3.5% does not exceed 300 MHz and is achieved at smaller (by 3-7 dBm) LR power values compared to that regarding the maximum efficiency points for converters with any number of photoactive p-n junctions.

Presence of subcells photocurrent mismatch for MJ MLPC also has a specific influence, as shown on (see figure 5). The limiting depth of the “down” modulation is limited by a smaller value. Since for the 6-junction structure at the “down” modulation mode with a depth of greater than 1%, an abrupt
decrease of the efficiency takes place due to that the PV converter voltage comes to zero. As a result, the AC voltage becomes lower by approximately 6% compared to that of a single-junction MLPC, and the efficiency – by 1.5%.

Figure 4. Dependence of AC voltage (a, d), bandwidth (b, e) and efficiency (c, f) of the investigated GaAs LPC with no photocurrent mismatch on incident laser power. Modulation type: (a-c) – 3.5% depth, “down”; (d-f) – 3.5% depth, “up”. Curves’ indexes correspond to the number of junctions.

Figure 5. Dependence of AC voltage (a, d), bandwidth (b, e) and efficiency (c, f) of the investigated GaAs MLPC with $\xi = 5\%$ photocurrent mismatch on incident laser power. Modulation type: (a-c) – 1% depth, “down”; (d-f) – 3.5% depth, “up”. Curves’ indexes correspond to the number of junctions.

4. Conclusions
The carried out analysis of the MLPC AC signal, bandwidth and efficiency in dependence on the modulation depth and LR power has shown that the modulation mode “down”, meaning the decrease of the LR flux with respect to the point of maximum power, is more useful. At the same time, it ensures the greater AC voltage amplitude, a wider bandwidth and the higher efficiency at one and the
same modulation depth. However, the presence of an inevitable photocurrent mismatch of MLPC subcells limits substantially the acceptable modulation depth and withstands realizing this advantage.

For a preset structure, size and the design of contact grid of PV converter the maximum bandwidth and also the device efficiency are, practically, constant and do not depend on the number of subcells. The increase in the number of photoactive p-n junctions allows raising the LR power, at which the high efficiency and fast operation are ensured.

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