Enhanced absorption distribution in waveguide integrated UTC-PD by means of dual injection

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In this work, the principle of dual injection for butt-coupled uni-traveling carrier photodiodes in a nanophotonic InP Membrane on Silicon platform is researched. Optical injection from both sides of the photodiode improves the optical power distribution compared to single side injection, in a device of the same size. Splitting the optical input power over both sides mitigates front-end saturation by decreasing the maximal carrier generation in hot-spots, resulting in increased maximum output currents before thermal failure. Multiple device length optima are determined based on theory and are validated using FDTD simulations. The simulations demonstrate a decrease in maximal carrier generation in hot-spots of up to 38%, an increase in optical power distribution uniformity of up to 24.8%, in combination with an improvement of 11.4% in responsivity compared to single injection PDs of the same size.

Introduction

High bandwidth photodiodes have demonstrated their use as opto-electric converters for optical interconnects and telecommunications [1]. Additionally, photodiodes can be used as high frequency signal generators acting as photomixer by the down conversion of signals in the optical domain. InP based uni-traveling carrier photodiodes (UTC-PDs) are a promising candidate to both of these applications by demonstrating high responsivity and bandwidth simultaneously [2]. The reported device in [2] demonstrates limited output power as the design suffers from front end saturation due to the butt-coupling nature of the PD, resulting in thermal failure [3].

Thermal failure is caused by Joule heating of the absorber [4], which depends on the dissipated power at increased optical intensities and is related to the current density in the absorber as well as the applied bias voltage [5]. Joule heating can thus be mitigated by improving the distribution of the optical field inside the absorber, which will prevent local hot-spots due to crowding of the local current density. Additionally, reducing the dependence of a high reverse bias voltage will also improve the thermal behavior of the device.

Multiple implementations of absorption distribution improvements have been demonstrated in literature, for various types of photodiodes. Some implementations use vertical directional coupling [6], or lateral directional coupling [7]. Additionally, multi-absorption region implements have been demonstrated [8], as well as multi-injection implementations [7], [9], [10]. Dual injection [7] is researched for the reported on UTC-PD [2], as this provides an elegant solution to mitigate front end saturation. Additionally, it is directly compatible with the existing UTC-PD design and only requires a circuit alteration.

This work covers the theory and design of a dual injection UTC-PD and provides simulation results in comparison to a single injection UTC-PD of the same length. From the results follow that using dual injection for optimized PD lengths results in increased distribution uniformity, responsivity and decreased maximum carrier generation rates with respect to single injection PDs of the same size.

Dual injection theory and design

The increased thickness inside the UTC-PD by the addition of the absorption layer, results in multi-mode behavior of the optical field, as can be seen in the lower plot in Fig. 1. The wavelength of this oscillation (λ_{osc}) can be calculated using coupled mode theory or numerical mode solvers and is then used to determine the optimal length of a dual-injection UTC-PD. When the length of the device corresponds to an integer n plus a half times this oscillation wavelength, the oscillating fields entering the PD from both sides are out of phase with each other resulting in improved optical field distribution. The optima can be determined using:

$$L_{\mathrm{opt}} = (n + 0.5)\lambda_{\mathrm{osc}} \qquad n = 1,2,3\,\ldots \tag{1}$$

Dual injection is achieved by splitting the optical power from an input waveguide over two waveguides, using a 3-dB splitter. These two waveguides are then connected to the sides of the UTC-PD such that the light is injected from both sides simultaneously as can be seen in Fig. 2. A downside of this approach is that the 3-dB splitter introduces insertion losses of around 0.6 dB [11], which impacts the effective responsivity of the device. Additionally, the 3-dB splitter is wavelength dependent which can influence the optical bandwidth of the total system.

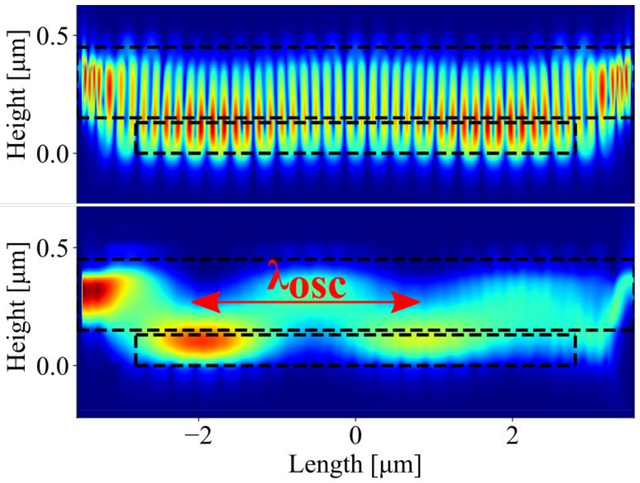

Figure 1: Optical field distributions for dual and single injection.

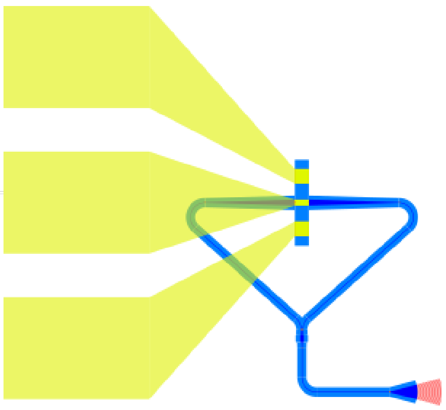

Figure 2: Layout of dual injection PD circuit.

The two counter propagating optical fields result in a standing wave interference pattern with a beat wavelength related to the effective index [12], as can be seen in the upper plot in Fig. 1.

The input fields are assumed to be of equal amplitude, phase and wavelength. In case fabrication inconsistencies result in a phase error, the effect on the standing wave pattern is limited to a phase shift of the standing wave [12], which has a negligible effect on performance. The standing wave interference pattern limits the theoretical improvement of field distribution, however, still significant improvements can be achieved as will be demonstrated in the following section.

Simulation results

Simulations are performed for 4 optimal dual injection device lengths, based on Eq. 1, as well as for single injection devices of the same length. The main figure of merit is the maximal carrier generation rate in hot-spots in the absorption region, as this is the cause of thermal failure. Additionally, the overall field distribution uniformity and device responsivity are also of interest. The commercially available software tool Lumerical FDTD is used to simulate the optical fields inside the PD and calculate the generated carriers due to absorption in the InGaAs region.

Maximal carrier generation & absorption uniformity

The maximal number of generated carriers (G_{max}) is determined by the intensity of the optical profile present in the absorption region. As dual injection splits the optical power over both sides of the PD, a decrease of G_{max} up to 50% is expected. The simulated G_{max} ratio between dual and single injection results for the 4 device lengths shown in Fig. 3 (orange) and demonstrate a reduction of up to 38% in hot-spots for dual injection devices. The overlapping residual light of the optical field from both sides after propagating through the device, limits the improvement for short devices.

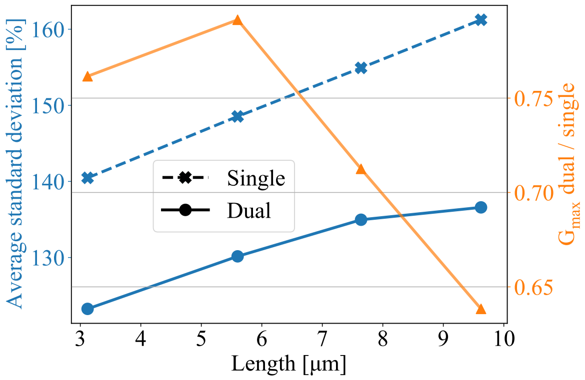

Figure 3: $G_{max}\frac{Dual}{Single}$ *and optical power distribution for 4 optimal device lengths.*

Figure 3 also shows the overall absorption uniformity (blue) of the field inside the absorption region. The uniformity is determined by taking the average standard deviation of all mesh point optical powers, divided by the average optical power. Improved uniformity decreases the average standard deviation, as is the case for the dual injection, which demonstrate a uniformity improvement of up to 24.8% for the longest device. The uniformity improvement is limited due to the standing wave pattern for dual injection.

Responsivity & power in absorption region

The responsivity of the UTC-PD is determined by summing all generated carriers for a single wavelength, which is then divided by the input power used in the simulation. It assumes that all absorbed photons result in electron-hole pairs. In principle, a dual injection and single injection PD of the same length should result in the same responsivity. However, the simulation results in Fig. 4 (blue) demonstrate an increase of the power present in the absorption layer of up to 10%, which results in an increase of responsivity of up to 11.4% for a device of 5.6 µm compared to single injection, as shown in Fig. 4 (orange). Simulations in a range around an optimal length are also performed, of which the responsivities are shown in Fig. 5. The figure shows a reduction of responsivity in case the length is suboptimal, due a reduction of power present in the absorption layer when the two injection fields are not fully out of phase. This demonstrates the responsivity sensitivity as a function of device length for which the optical fields are sufficiently out of phase, and results in a tolerance window of ±100 nm in which responsivity is at least as good as the single injection device.

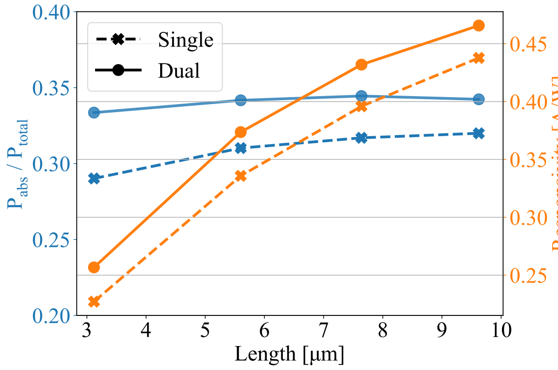

Figure 4: Pabs / Ptotal and responsivity for 4 lengths.

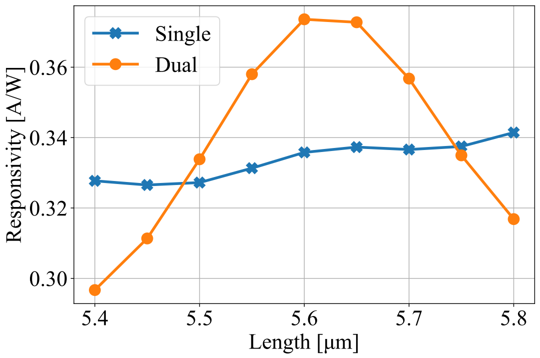

Figure 5: Responsivity around optimal length.

Conclusion

Improving the optical absorption profile in butt-coupled UTC-PDs by means of dual injection is investigated in this work, and has proven to mitigate high carrier generation in local hot-spots while simultaneously improving responsivity compared to single injection. The optical field oscillation introduced by the increased local waveguide thickness in the PD results in multiple optimal lengths for dual injection PDs. Four of these lengths have been simulated and demonstrate a decrease of maximal carrier generation of up to 38% in hot-spots, an increase in optical power distribution uniformity of up to 24.8% for the longest device, and an improvement of 11.4% in responsivity for a device of 5.6 µm compared to single injection PDs of the same size.

Acknowledgement

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