Analysis and Design of *p-i-n* Traveling-Wave Photodetectors for High Power and Wide-Bandwidth Applications

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Traveling-wave photodiodes, achieving a larger bandwidth-efficiency product than classical vertically illuminated photodetectors, are the key elements for ultra-wide bandwidth optical links. They can absorb high power levels, allowing to design wide dynamic range systems. In this paper, both the velocity mismatch and electrical signal reflections at both input and output device ends are investigated. Design criteria for long absorption length photodiodes, taking into account transit-time limit and microwave losses, are derived. As broadband applications require a thin intrinsic region, while wide absorbing surface are needed to reduce insertion losses, a trade-off between bandwidth and coupling efficiency has to be reached.

Introduction

Ultra-wide bandwidth photodetectors, allowing both high operating frequencies and a large quantum-efficiency, are the key elements of the future optical communication systems. Research has already been done on both *p-i-n* [1]-[3] and metal-semiconductor-metal (MSM) photodiodes [4]. For well designed *p-i-n* diodes, it is commonly stated that the optimal bandwidth results from a trade-off between the carrier transit-time and the junction capacitance. Unfortunately for broad bandwidth applications, sub-micron intrinsic regions are required so that the fraction of absorbed light inside the active layer decreases. Moreover, conventional vertically-illuminated detectors (VPDs) are not able to handle large illumination powers because of the electric field screening effects induced by high carrier concentrations [5],[6]. Thus, in order to improve the bandwidth quantum-efficiency product, while increasing the saturation photogenerated current, edge-illuminated devices such as traveling-wave photodiodes (TWPDs) [8] or waveguide photodetectors (WGPDs) [7] should be used.

Limits on power absorption

In order to investigate the power-handling capability of VPDs, a $GaAs\text{-}In_{0.3}Ga_{0.7}As\text{-}GaAs$ heterojunction *p-i-n* photodiode with a doping concentration of 1×10^{18} for both p^+ and n^+ regions, and of 1×10^{15} for the n^- intrinsic layer, has been considered. The electric field has been determined in correspondence of several illumination intensities, by numerically solving the drift-diffusion equations. As shown in Fig. 1, when increasing the light intensity, the electric field within the depletion region begins to decrease. On the other hand, it increases at the hetero-interface between the p^+ and the n^- layers. As the electric field decreases, the carrier density within the intrinsic region grows rapidly, further reducing the electric field. This positive feedback degrades the device response as the carriers are swept out slowly. Although the bias voltage can be increased, a large reverse bias must be avoided as the semiconductor material's breakdown can be reached. Moreover at high electric fields the band-to-band tunneling [9] limits the photodiode response as a

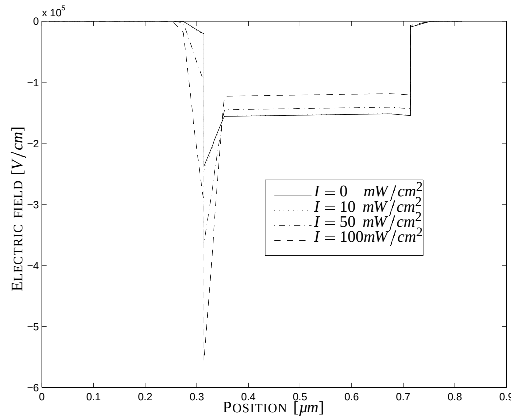


Figure 1: Electric field for several light intensities for a reverse bias of $5V$.

significant current begins to flow through the junction. Since the electrical output power is directly proportional to the illuminated volume, a large photogenerated current can be obtained by increasing the intrinsic layer thickness and the illuminated surface. Unfortunately, when thicking the depletion region, the carrier transit-time increases, while large surfaces correspond to high *RC* time constant. Both these effects strongly reduce the photodetector bandwidth.

In order to achieve a large bandwidth-efficiency product while handling high optical powers, TWPDs should be used. However, these devices are usually designed with large absorption coefficients in order to strongly reduce the intermodulation distortions, due to the space-charge effect. Consequently, the incident light is absorbed within few micronmeters. Thus, large output saturation currents are only possible by reducing the modal optical absorption, leading to wide absorbing volume. It should however be noted that, if the TWPD is not perfectly matched, the waveguide length cannot be increased indefinitely without degrading the bandwidth. Thus, long absorption length TWPDs suffer not only from a serious velocity mismatch between the optical and the electrical waves traveling along the device, but also from signal reflections at the input and output ends of the structure. On the other hand, the length of perfectly matched devices, should be determined in order to absorb at least 95% of the light, accordingly to the following formula

$$1 - e^{-\Gamma(z)\,\alpha_o\,L} > 0.95 \qquad (1)$$

where Γ is the optical confinement factor within the intrinsic layer, α_o is the optical absorption coefficient, and L is the device length.

Electrical and optical wave velocities

The general outline of a TWPD consists of an electrical coplanar transmission line (CPW) coupled to an optical waveguide. As the waveguide geometry and its material composition are determined in order to distribute the incident power density along the device and to maximize the coupling efficiency, the group velocity of the optical traveling wave is fixed. Its value depends on the optical effective index n_o, which approximately ranges from that for the core material to that for the cladding. Thus, the only way to insure the velocity matching between optical and electrical waves, consists of tuning the RF phase velocity by varying the electrode dimensions. For *p-i-n* TWPDs, considered in this paper, when the transverse component of the electric field is much larger than the longitudinal one, and the depth penetration of quasi-static field is small compared with the skin depth of the substrate, the propagation mode is approximatively TEM. Hence, the microwave velocity can be written as

$$v_e = \frac{c}{\sqrt{\varepsilon_{eff}}} \tag{2}$$

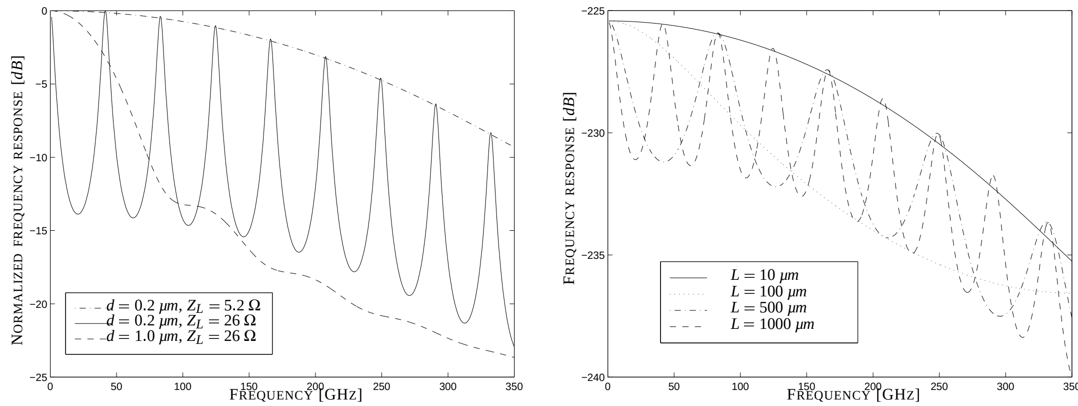
where c is the velocity of the light and ε_{eff} the total effective permittivity. It is possible to show that by increasing the intrinsic region thickness d, the microwave losses begin to decrease. Consequently, the phase velocity of the RF signal increases. On the other hand, the microwave signal velocity can be reduced by increasing the waveguide width w. Thus, by an opportune choice of both depletion region thickness and waveguide width, the electrical propagation velocity can be tuned over a wide range. It should however be noted that large d values increase the carrier transit-time, while shrinking w, the insertion losses, when coupling the light into the waveguide, can be large.

Bandwidth

The bandwidth limitations of long absorption length TWPDs have been analyzed by considering both the velocity mismatch between the optical and the microwave signals, and the electrical reflection which can occur at the device input and output ends. Fig. 2(a) shows the influence of the depletion region thickness d on the bandwidth, for several values of the load. Both dot dashed line and dashed line have been obtained by perfectly matching the traveling-wave photodiode at both input and output ends. As the characteristic impedance depends on d, the output load Z_L has a different value for the two simulated curves. The solid line shows the voltage response obtained for $d = 0.2\mu m$, but with the output load impedance Z_L that does not exactly match that of the TWPD. Due to mismatch, a strong ripple occurs in the frequency response. When the load at the end of the structure does not entirely absorb the forward wave, the length of the TWPD greatly influences the bandwidth. This situation is illustrated in Fig. 2(b). The frequency response has been calculated for several device lengths, when the terminating load is different from the characteristic impedance Z_c. When the TWPD is electrically long, reflections at the input and output ends produce multiple echoes that degrade the signal transmission.

Conclusions

In this paper, we determine the main bandwidth limitations for high-speed and large power-handling capability TWPDs. By matching the optical group velocity to the electrical phase velocities, no usual *RC* time constant can be defined. Consequently, TWPDs can attain higher bandwidth than both VPDs and WGPDs, simply by shrinking the intrinsic region thickness. For long absorption length applications, TWPDs must be electrically matched in order to eliminate reflection at the input and output ends of the device.



(a) (b)

Figure 2: Output voltage of input open-ended TWPD, for (a) three different combinations of intrinsic thickness d and output load Z_L and (b) for four different device lengths. (photodetector width $w = 4\ \mu m$, optical wavelength $\lambda = 1.33\ \mu m$, refractive index $n = 3.5$, reverse bias voltage $V_0 = 10\ V$).

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