PHOTODIODE FOR COHERENT DETECTION : MODELING AND EXPERIMENTAL RESULTS

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Résumé - En détection cohérente, la puissance optique de l'oscillateur local peut conduire le photodétecteur en régime de forte injection. Des dégradations de performances du dispositif peuvent alors être constatées à partir de simulations numériques et de mesures.

Abstract - In coherent detection, the optical power of the local oscillator can lead the photodetector in the high injection regime. Degradation of the device performance can then be observed from numerical simulations and experiments.

1 - INTRODUCTION

Coherent detection can substantially improves optical communication system performances [1]. Wavelength stabilized semiconductor lasers provide for the necessary local oscillator. Optical power of the local oscillator greater than the radiant power corresponding to the optical signal, yields better signal to noise ratio.

Photodetectors design is a compromise between different parameters such as sensitivity, response time, capacitance, gain, noise. The intrinsic material width of a PIN photodiode must be such that sufficient light is absorbed (sensitivity), that the free carriers thus generated are quickly collected (response time), driven at their top velocity by an uniform electric field, and so that the junction capacitance is low to limit RC time constant.

At high level of optical illumination, free carrier densities can be such that the electric field in PIN photodiodes is no longer uniform and exhibit low and high values areas. This behaviour is expected to affect the response time of the device.

The goal of this study is to determine the influence of the optical power on the photodiode performances, in coherent detection, when a high radiant optical power shines on the photodetector, mixed along with the transmitted low level signal from the fiber output. The operation of Si, Ge, GaInAs/InP photodiodes under low and high optical power are described in terms of sensitivity, linearity, response time and diode capacitance as predicted by numerical simulation and confirmed by measurements.

2 - MODELING AND NUMERICAL METHODS

Unidimensional numerical simulation of PIN photodiodes are performed, using finite difference methods, solving the following set of equation that describes the behaviour of semiconductor devices. This set includes Poisson equation, electron and hole continuity equations and current formulation. Thermal generation recombination term as well as optical generation are taken into account [1].

Fig.1 - Electric field distribution in Ge PIN photodiode, with high and low field value.

$$\left\{ \begin{array}{l} \text{div } \epsilon \vec{\text{grad}} \varphi = q \cdot (n - p - C) \\ \frac{\partial n}{\partial t} = \frac{1}{q} \cdot \text{div} (n \mu_n \vec{\text{grad}} E_{Fn}) - U_{\text{SHR}} + G_{\text{opt}} \\ \frac{\partial p}{\partial t} = -\frac{1}{q} \cdot \text{div} (p \mu_p \vec{\text{grad}} E_{Fp}) - U_{\text{SHR}} + G_{\text{opt}} \end{array} \right. \text{ and } \left\{ \begin{array}{l} G_{\text{opt}}(x) = \int_{\lambda} \alpha(\lambda) \cdot \exp[-\alpha(\lambda) \cdot x] d\lambda \\ U_{\text{SHR}} = \frac{n \cdot p - n_1 \cdot p_1}{\tau_n (p + p_1) + \tau_p (n + n_1)} \end{array} \right.$$

With n , p ; τ_n , τ_p ; μ_n , μ_p ; E_{Fn} , E_{Fp} are respectively electron and hole carrier densities, carrier lifetimes, mobilities and Fermi levels. The electrostatic potential is φ . The dielectric constant is ϵ and the fixed charge density is C . Thermal generation recombination is described by the Shockley-Hall-Read formulation U_{SHR} and the external optical generation $G_{\text{opt}}(x)$ takes into account the α absorption value at position x , as a function of wavelength λ .

The set of equation is linearized and solved within an uncoupled scheme of resolution, using a variable implicit method to solve the transient case.

Fig.1 - Electric field distribution in Ge PIN photodiode, with high and low field value.

3 - NUMERICAL SIMULATION RESULTS

At high optical power, the electric field in the intrinsic layer of the PIN photodiodes is no longer uniform (Fig 1). As the optical power increases, larger potential drops arise at the P^+v and vN^+ junctions and increasingly wider areas of low electric field spread in the intrinsic material. The peak value of the electric field does not modify carrier velocities and is insufficient to enhance avalanche. With electric field as low as a few kV/cm, carrier velocities can drastically decrease and lead to large transit time of the carriers across the intrinsic layer. With slow drift, in poor quality material, the carriers can suffer from recombination before being collected and thus sensitivity lowers. The obtained electric field distribution is equivalent to that of two junctions. The sum of the corresponding space charge regions is then smaller than the intrinsic layer width and it can be expected that the overall capacity increases.

Accurate computation of the capacity of the device is performed taking into account the local variation of the electric charge and of the displacement vector between two close bias [2]. Evolution with optical power is given in Fig 2.

Fig.2 - Increase of PIN photodiodes capacities, with increase of the local oscillator radiant power, as obtained by numerical simulation.

Numerical simulations show that for optical power larger than 10^{21} photons/s/cm² the behaviour of the photodiodes can be far different than the low optical regime such photodiodes had been designed for. An optical power of 5 mW shining over 100 μm² (surface of the core of a monomode fiber) is equivalent to some $5 \cdot 10^{22}$ photons/s/cm².

4 - MEASUREMENTS AND IMPROVED EQUIVALENT CIRCUIT

The complex impedance of the photodiodes has been measured on a 50 Ω load, using a network analyser, through S_{11} parameter, after proper calibration, in the .1 - 2 GHz band width.

Fig.3 - Improved equivalent circuit for Ge photodiode and value extraction method provide good impedance fit in the .1-2 GHz range.

The different elements of the equivalent circuit of the photodiode (junction and package capacitances, junction and serial resistances, wire inductances) are obtained through an

improved parameter extraction method. This method allows to determine the best fit values of the different elements of the equivalent circuit described by the operator without any prior knowledge of the values or ranges. The equivalent circuit of the photodiodes had to be completed by elements such as wire inductance or chip to package capacitance to obtain correct fit as shown in figure 3.

The variation of the junction capacitance and serial resistance of the photodiode have thus been extracted for optical power at $1.3\ \mu\text{m}$ ranging from obscurity to $4.4\ \text{mW}$ for the GaInAs/InP diode ($3.5\ \text{mA}$ photocurrent, $7.5 \cdot 10^{20}\ \text{photons/s/cm}^2$) and $9\ \text{mW}$ for the Ge diode ($7\ \text{mA}$, $1.5 \cdot 10^{21}\ \text{ph/s/cm}^2$).

$\triangle$ GaInAs/InP PIN diode $\square$ Ge PIN diode

Fig.4 - Relative junction capacitance increase versus diode photocurrent, as $1.3\ \mu\text{m}$ local oscillator radiant power increases. The junction capacities are obtained from microwave measurements and improved equivalent circuits of photodiodes.

As it can be seen in figure 4, the junction capacity of the Ge and GaInAs/InP photodiodes continuously increase with increasing optical power. The time constant (junction capacitance - serial resistance product) continuously increases but for such optical power is still below transit time.

5 - CONCLUSION

Numerical simulations of photodiodes predict that above an optical power corresponding to flux greater than $10^{21}\ \text{photons/s/cm}^2$, the response time and the junction capacitance will continuously rise. Experimental measures confirm this increase of the capacitance and $R_s \cdot C$ time constant. For standard diode active diameter ($70\ \mu\text{m}$), the optical power delivered by a conventionnal semiconductor laser (a few mW) is beneath the limit for which photodiode performances would shrink.

6 - REFERENCES

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