The Scattering Parameter Analysis Using the Circuit Model of UTC-PD

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Abstract. A small signal equivalent circuit model of uni-traveling carrier photodiode (UTC-PD) is developed from integral carrier density rate equation and parasitics are included with it. The technique to obtain scattering parameters from circuit model is given and simulation results are in good agreement with the measurement.

Keywords: Circuit model · Photodiode · Scattering parameter

1 Introduction

Uni-traveling carrier photodiode (UTC-PD) is promising as a key device for millimeter (mm) wave photonic transmitter [1]. Fiber to wireless low power transmitter node can be designed with such device for the access node in next generation 5G pico/femto-cellular wireless transmission in the license-free mmwave band [2]. It can enhance the network capacity for broadband operation. To optimize the device performance, it is essential to develop a suitable model of the device. The existing circuit models of UTC-PD [3, 4] are mostly based on observations and circuit elements are extracted from the measured output reflection coefficient [4].

In this work, the integral carrier density rate equation is extended to develop small signal AC circuit model. The model can be implemented in SPICE or CAD-like circuit simulator. The S_{22} parameter which quantifies the output reflection coefficient is obtained employing small signal circuit model and the results are verified with the experiment results.

The chapter is organized as follows: Sect. 2 provides derivation of the small signal intrinsic and parasitic circuit model of UTC-PD. Scattering parameters are evaluated and verified with the experimental values in Sect. 3 and conclusions are drawn in Sect. 4.

2 Derivation of the Circuit Model

Schematic of vertically illuminated $In_{0.53}Ga_{0.47}As/InP$ UTC-PD layer structure and the detail operating principle of UTC-PD can be found in [1, 5], respectively. The following subsection describes small signal circuit model of UTC-PD and how the scattering

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parameters can be obtained from the circuit model. The continuity equation of the integral photogenerated carrier density $h(t)$ for electrons in the photo-absorption region of UTC-PD can be expressed by [5].

$$\frac{\mathrm{d}h(t)}{\mathrm{d}t} = Q_{\mathrm{in}}(t)\left[\exp\left\{-(m+\beta_1)\frac{h(t)}{A} + (mN_0 - \beta_0)W_{\mathrm{A}}\right\} - 1\right] - \frac{h(t)}{\tau} - \frac{\mu_n E_{\mathrm{indo}} h(t)}{W_{\mathrm{A}}} \tag{1}$$

The description of the parameters in Eq. (1) and their values can be found in [6] which will be used in the simulation.

2.1 Small Signal Circuit Model

When a time varying light (photon flux) with suitable wavelength and energy is incident on UTC-PD then carriers $h(t)$ are generated within it. The modulated integral photogenerated carrier $h(t)$ can be expressed by

$$h(t) = h_{\mathrm{dc}} + \Delta h(t) \tag{2}$$

where h_{dc} is the DC part and $\Delta h(t)$ is the AC part of carrier density variation. Under small signal condition, $\Delta h(t)$ is small. Hence, time varying exponential term ($\mathrm{e}^{\Delta h(t)}$) in Eq. (1) can be approximated as $(1+\Delta h(t))$. Substituting the above approximation and following few mathematical steps, the time varying parts are separated out to obtain Eq. (3).

$$\frac{d(\Delta h(t))}{dt} = \Delta Q_{\mathrm{in}}(t)\left[e^{b}.e^{-\left\{\frac{(m+\beta_1)}{A}\right\}h_{\mathrm{dc}}} - 1\right] - \left(\frac{1}{\tau} + \frac{\mu_n E_{\mathrm{ind0}}}{W_{\mathrm{A}}}\right)\Delta h(t) \tag{3}$$

2.2 Extraction of Circuit Parameters

Equation (3) can be expressed in the circuit form as follows:

$$C\frac{\mathrm{d}v(t)}{\mathrm{d}t} = i_{\mathrm{ac}}(t) - \frac{v(t)}{R} \tag{4}$$

Comparing Eq. (4) with Eq. (3), the AC current source $i_{\mathrm{ac}}(t)$ at 1550 nm wavelength is given by

$$i_{\mathrm{ac}}(t) = \Delta Q_{\mathrm{in}}(t)\left[e^{b}.e^{-\left(\frac{(m+\beta_1)}{A}h_{\mathrm{dc}}\right)} - 1\right] \tag{5}$$

To find the voltage v(t) from the dimensionless device intrinsic parameter $\Delta h(t)$, we assume

$$v(t) = \frac{AE_{\mathrm{ind0}}\Delta h(t)}{W_{\mathrm{A}}} \tag{6}$$

The other parameters are

$$R = \left(\frac{W_{\mathrm{A}}}{A\tau E_{\mathrm{indo}}} + \frac{\mu_n}{A}\right)^{-1} (\text{in Ohm}),$$
$$C = \frac{W_{\mathrm{A}}}{AE_{\mathrm{indo}}} (\text{in Farad}) \text{ and}$$
$$g = \frac{qW_{\mathrm{A}}}{(\tau_{\mathrm{g}} + \tau_{\mathrm{C}})AE_{\mathrm{indo}}} (\text{in mho}) \tag{7}$$

The Eq. (3) can be implemented using circuit elements given by Fig. 1a.

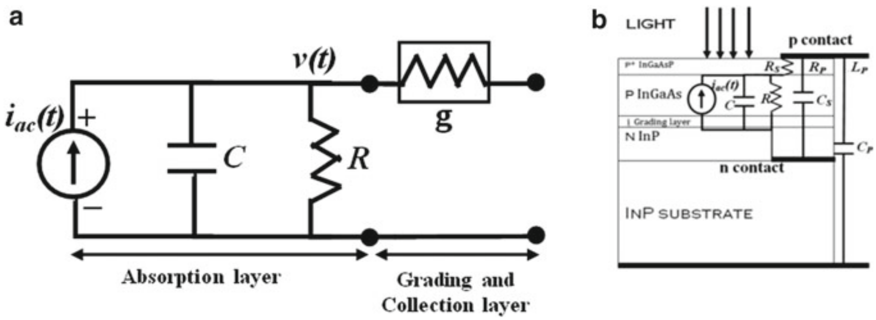

Fig. 1 **a** Small signal circuit model of intrinsic UTC-PD and **b** cross-section of UTC-PD with parasitic element

The circuit element '*g*' is included at the output in Fig. 1a in order to incorporate the effect of grading layer in the model.

2.3 Inclusion of Electrical Parasitic

High frequency performance of the device can be significantly affected by the chip and package parasitics. The parasitic elements are included in circuit model as shown in Fig. 1b. R_{S} is the substrate resistance, C_{S} is the chip capacitance due to leakage, bonding wires due to packaging causes inductance L_{P} and provides resistance R_{P}. The package capacitance C_{P} arises due to the close proximity of bonding wires which is significant at high frequency.

3 Simulation Results

Circuit as shown in Fig. 1a, b is implemented in Capture CIS OrCAD_10.5 simulation software. The SPICE simulation procedure to extract the *S* parameters of a two port network is presented briefly. It may be noted that the method is applicable for *n*-port network also.

S parameters measure the ratio of the powers of the incident and the reflected signals. The incident and corresponding reflected signals are defined as a_1, a_2 and b_1, b_2, respectively, at the input port 1 and output port 2. The scattered waves are related to the incident waves by the following matrix form:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \tag{8}$$

The S_{ij} coefficients are dimensionless ratios. S_{22} is the output reflection coefficient can be calculated as

$$S_{22} = \frac{b_2}{a_2}\bigg|_{a_1=0} = \frac{2Z_L}{Z_L + Z_0} - 1 \tag{9}$$

where Z_L is the device output impedance and Z_0 is 50 Ω. Similarly, S_{21} is the forward transmission coefficient and is defined as the ratio b_2/a_1.

$$S_{21} = \frac{b_{b_2}}{a_1}\bigg|_{a_2=0} = \frac{2V_{\text{out}}}{V_{\text{in}}} \tag{10}$$

In the simulation, two sub-circuits are required by SPICE to measure the transmitted and reflected powers at the two ports of small signal circuit of Fig. 1. Two S parameters namely S_{21} and S_{22} are important to us. The other two parameters namely S_{12} will be equal to zero for a photodetector [7] and S_{11} is the input reflection coefficient for the optical port which is unimportant as it does not contribute to output photocurrent. To measure the forward transmission coefficient (S_{21}), the output impedance should be matched with the input impedance and the transmission coefficient is the output voltage multiplied by 2. In order to measure S_{21} of the circuit model, a small measuring sub-circuit called "TRANSMIT" is employed. "TRANSMIT" consists of a voltage controlled voltage source (VCVS) (denoted by E) having gain of 2 and associated circuit provided by SPICE as shown in Fig. 2a. During measurement of S_{21}, the hierarchical port "CKT" connects circuit model of UTC-PD given in Fig. 1b and the other port "STR" is declared as "hidden pin". Similarly, the sub-circuit arrangement named "REFLECT" as shown in Fig. 2b is used to measure the output reflection coefficient S_{22}. The reflection coefficients are the input voltage multiplied by 2 minus AC unity. So, VCVS has a gain of 2. Here, also the interface pin CKT is used to connect with the measuring UTC-PD circuit. The hidden pin SRE is left unconnected. There is a provision to apply the bias voltage at V1 for active circuits which is set to zero in our simulation.

S_{22} and S_{21} are measured by connecting two customized hierarchical sub-circuits "TRANSMIT" and "REFLECT", respectively, with UTC-PD circuit port by off-page connectors using SPICE.

The simulated S_{22} parameter is evaluated with frequency from the circuit model in Fig. 1b using SPICE. The magnitude and phase plot of the output reflection coefficient S_{22} versus frequency is shown in Fig. 3a, b, respectively.

Similarly, S_{21} the optical to electrical frequency response is plotted in Fig. 4. The variation of S_{21} versus frequency is agreed well with the experimental result [8] as shown by the arrow in Fig. 4.

In order to plot S_{22} parameter in a conventional way such as in a Smith chart, it is required to evaluate from Fig. 1b by using MATLAB. The output reflection coefficient

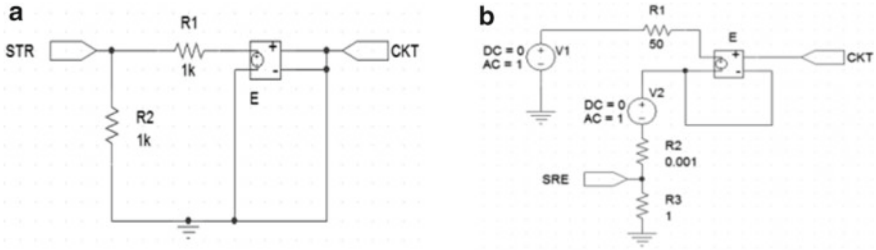

Fig. 2 SPICE sub-circuit model **a** TRANSMIT and **b** REFLECT, respectively, to measure transmission S_{21} and reflection coefficient S_{22} coefficient

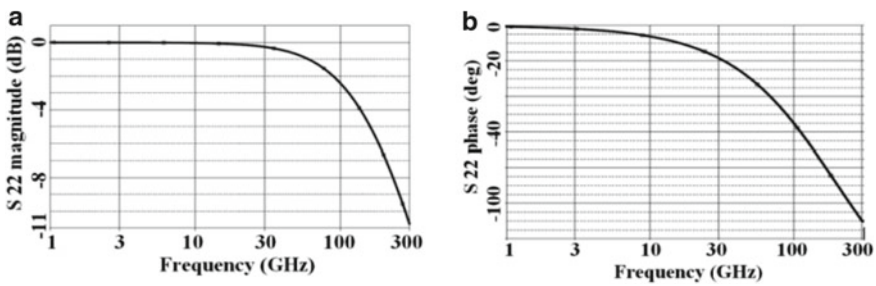

Fig. 3 **a** Magnitude and **b** the phase of output reflection coefficient S_{22} with frequency

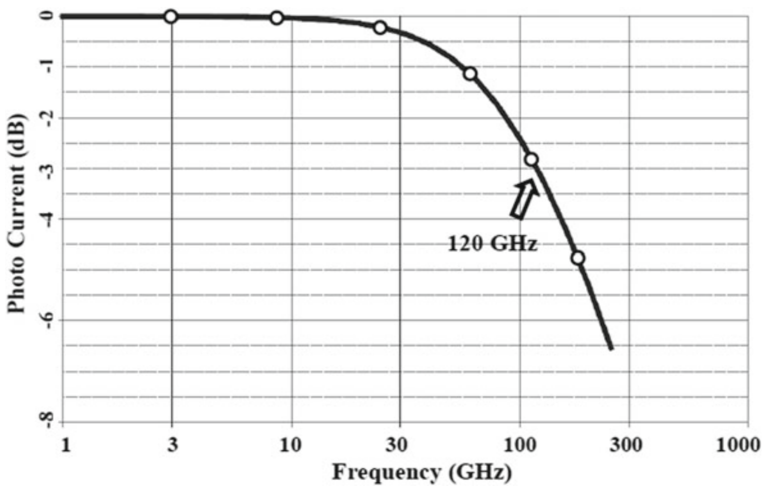

Fig. 4 S_{21}, the optical to electrical frequency response of UTC-PD

(S_{22}) is calculated using the relation

$$S_{22} = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{11}$$

The output reflection coefficient is derived in the frequency range 1–120 GHz at two different bias voltages 0 and −2 V from the small signal circuit model of UTC-PD. The output reflection coefficients with frequencies are shown by the Smith chart in Fig. 5. The simulation results plotted by the dashed line closely matches the experimental data [9] shown by cross symbols. The extracted parasitic values are given in Table 1.

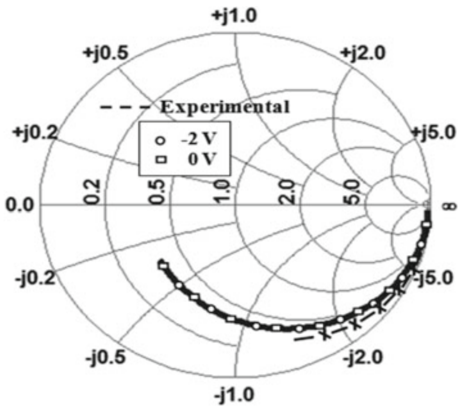

Fig. 5 Output reflection coefficients of $In_{0.53}Ga_{0.47}As$/InP UTC-PD for the frequency range from 1 to 120 GHz (circles and squares) using the small signal circuit simulation model and that of GaAs/$Al_{0.15}Ga_{0.85}As$ based UTC-PD from 1 to 15 GHz (cross dotted line) using simulation and experiment

Table 1 Extracted values of parasitic from small signal circuit model

Parasitic circuit elements	Values
R_S	1 Ω
L_P	0.015 nH
$(C_S + C_P)$	0.05 pF
R_P	10 Ω

4 Conclusions

We have developed a time varying small signal equivalent circuit model of UTC-PD from carrier density rate equation. The circuits are implemented in a SPICE simulator. Chip and package parasitics of the device are readily incorporated as lumped elements into the model. The scattering parameters of UTC-PD which quantify the input–output transmission and reflection coefficients of the device are obtained from the developed model. Close agreement of the simulation results with the measured values shows that the model can be useful as a tool to optimize UTC-PD performance in mmWave transmissions.

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