Circuit Model of UTC-PD with High Power and Enhanced Bandwidth Technique

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Abstract—**An electrical equivalent circuit model of InGaAs/InP uni travelling carrier photodiode is presented. The model is suitable to be built on any electrical circuit simulator to perform design and optimize the device parameters. We have shown a novel technique of increasing bandwidth of the device by inserting a small shunt inductance in series with the load without sacrificing the device output photocurrent and linearity to a large extent.**

Index Terms— circuit model, photodiode, inter-modulation

I. INTRODUCTION

Integrated photonic transmitter based on uni travelling carrier photodiode (UTC-PD) with built-in amplifiers and antennas on the same guiding structure is attractive due to its high power, bandwidth and capability of generating millimeter wave (MMW) signal at $75 - 180$ GHz range. Such approach facilitates radio over fiber based microcellular system promises higher spectrum utilization and high capacity. In order to optimize the system performance for the integrated UTC-PD with other photonic and radio frequency (RF) components, elegant physics based electrical circuit model of UTC-PD is needed.

Research efforts have mainly been made to optimize the device performance through various experiments involving UTC-PD [1]-[3]. Among the notable work A. Beling *et. al.* [1] developed a simplified circuit model of UTC-PD; however, transit-time effects of the carriers were not considered in the analysis. As a result bandwidth dependency on absorption layer width could not be studied. F. M. Kuo *et. al.* [2] presented an equivalent circuit model, however, the impacts of increased device bandwidth on inter modulation distortion and linearity has not been analyzed. M. Chtioui *et. al.* [3] reported use of thick absorption layer (1200 nm) to achieve high photocurrent at the cost of low bandwidth less than 30 GHz and moderate linearity. All these works show that there is a gap between achieving high photocurrent and high bandwidth due to inherent transit time limitation of the device. In this work, we focus on this aspect that how to increase the device bandwidth without sacrificing its output photocurrent and linearity to a large extent. In order to enhance the bandwidth we propose to connect a shunt inductance in series with the load which may be easily implemented in integrated circuit fabrication of the device. This is a well known technique of increasing bandwidth in electronic video circuit. We have investigated its effect with our comprehensive physics based UTC-PD equivalent circuit model. The model is derived from the simple integral rate equation [4] involving electron and hole movement in UTC-PD. Internally generated self-induced field and dominant drift movement of photo generated carrier is considered in the model. The model sub-blocks are

implemented by current controlled or voltage controlled sources whose gains are equivalent to the transfer function of different sub-structures of UTC-PD. The advantage of this model is that the physical parameters of the device can be controlled with the help of circuit elements. The frequency response obtained from this model is validated with the experimental results.

II. THEORY AND MODELING

Schematic of UTC-PD is shown in Fig. 1. If light (1550nm) is illuminated on a UTC-PD then the photo-absorption takes place only in the p-type InGaAs layer. The confined photo-generated majority carrier hole relaxes without transport where as minority electrons diffuse through the p-type absorption layer and drift to the n-type InP collection layer.
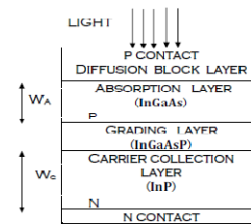

Fig. 1. Schematic of top illuminated UTC-PD

A. Circuit Modeling of UTC-PD

The total frequency response of UTC-PD can be derived from the frequency response [4] under small signal short circuit condition is

$$J_{tot}(\omega) = \frac{W_A}{W}\left[\frac{J_{DC}}{1+j\omega\tau_A}\right]\cdot\left[1 - \frac{j\omega\tau_R}{1+j\omega\tau_R}\left(1 - \frac{k}{J_{DC}}\right)\right] + \frac{W_c}{W}\left[\frac{J_{DC}}{1+j\omega\tau_A}\right]Sinc\left(\frac{\omega\tau_c}{2}\right)exp\left(-\frac{j\omega\tau_c}{2}\right) \quad (1)$$

Equation (1) contains some constant and frequency dependent terms which are multiplicative or additive to each other. To develop an electrical circuit model of (1), each additive and multiplicative term are connected in series and parallel respectively. The negative sign can be realized by connecting the positive end of one sub-circuit with the negative end of the other sub-circuit block. A constant term as $[\frac{W_A}{W}J_{DC}]$ is realized by placing a current controlled current source (CCCS) of gain $[\frac{W_A}{W}J_{DC}]$ as shown in Fig. 2(a). The frequency dependent terms are realized by inductive or capacitive circuits. To derive the admittance term $\frac{1}{1+j\omega\tau_A}$, a current to voltage converter is required. This term is realized by current controlled voltage source (CCVS) of unit gain followed by a series RL circuit as

shown in Fig. 2(b). Similarly, the term $\frac{j\omega\tau_R}{1+j\omega\tau_R}$ is implemented by a RC circuit replacing L by C in Fig. 2(b). The complete equivalent circuit model of UTC PD governed by (1) is shown in Fig. 3(a). Electron-hole pair generation due to uniform optical excitation is represented by a current source. The upper branch of the circuit of Fig. 3(a) represents absorption region where series inductance L represent the carrier transit time (τ_A) and C represents the relaxation time (τ_R) of photo-generated holes through absorption layer. Lower branch represents collection layer.

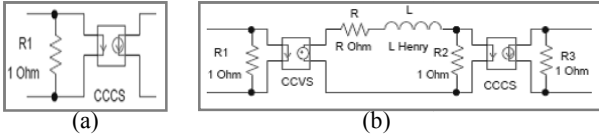(a)   (b)

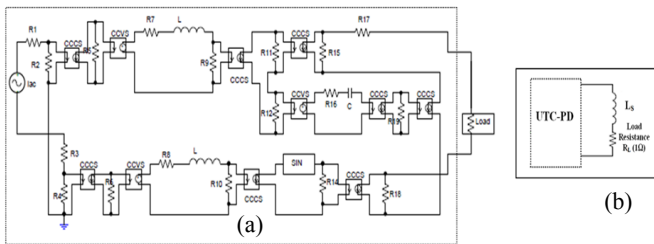Fig. 2. Circuit realization of different functional block of UTC-PD

Fig. 3. (a) Equivalent circuit model of UTC PD and (b) load in with shunt inductance L_S for bandwidth enhancement of UTC PD

III. RESULTS AND DISCUSSIONS

Circuit model of UTC-PD is implemented in Capture CIS OrCAD_10.5 environment. The device to be useful as photonic-wireless transmitter the linearity of the device is very important. Accurate estimation of inter-modulation products is obtained through transient analysis of the device and its Fourier transform. Another important factor such as high output photocurrent can be achieved through increased thickness of the absorption layer; however, this reduces the bandwidth of the device. In order to enhance the bandwidth we propose connecting a shunt inductance L_S in series with the load as shown in Fig. 3(b). In integrated circuit solution, this additional inductance may be incorporated by means of short-end coplanar waveguide (CPW) stub [5], which also acts as impedance transformer [6] to the transmitting antenna input impedance.

A. Output photocurrent and frequency response

In the simulation, the input optical power is kept fixed at 10 dBm. The black dot circles and black diamond shape points in Fig. 4 are respectively for the 3-dB cutoff frequencies (f_{3dB}) and output photocurrent obtained from the circuit simulation of Fig. 3(a). The corresponding analytical plot of f_{3dB} and photocurrent is shown by green squares and blue circles respectively. Experimental [4] value of bandwidth at 220 nm absorption layer width (W_A) closely matches with the simulation which is shown by red star. When shunt inductance L_S (= 10 pH) is incorporated in series with load as shown in Fig. 3(b), the f_{3dB} point increases (shown by red circles) but photocurrents remain same (shown by black diamond points). The increase of f_{3dB}
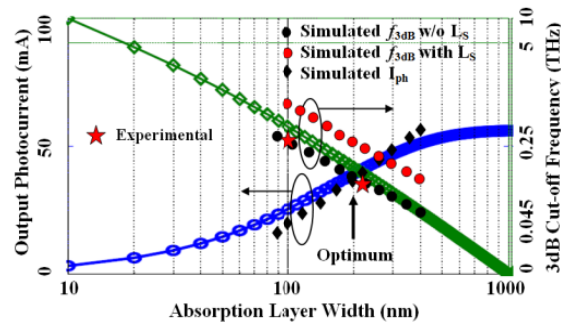

Fig. 4. Photocurrent and f_{3dB} frequency at different absorption layer width with and without L_S

is about 200 GHz with output photocurrent remains at 35 mA when W_A is 200 nm. At larger W_A (400 nm) f_{3dB} increases from 43 GHz to 123 GHz when L_S is incorporated in the load and the corresponding output photocurrent obtained is 62 mA. This high f_{3dB} and photocurrent could not be achieved without shunt inductor L_S.

B. Enhanced response and intermodulation distortion

Frequency response of UTC-PD obtained from the circuit model for different values of L_S is shown in Fig. 5(a). The f_{3dB} obtained are 43.8 GHz, 57.35 GHz, 80 GHz and 123 GHz for different values of L_S equal to 0 pH, 1 pH, 1.5 pH, 10 pH respectively at W_A equal to 400 nm. Increase of L_S larger than 10 pH does not further improve the bandwidth. Then third order inter-modulation distortion (IMD_3) is carried out without and with L_S (= 10 pH). The third order intercepts point (IP_3) without and with L_S is 60 dBm and 56 dBm respectively which are acceptable.

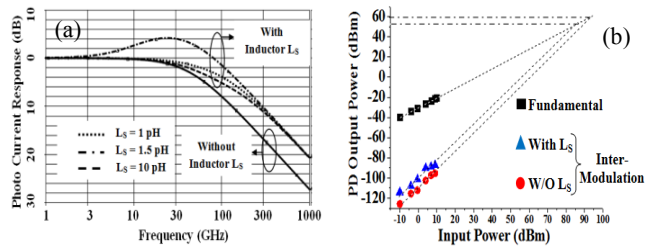Fig. 5. (a) Frequency response of UTC-PD at different L_S and (b) IP_3 at 60 GHz with and without L_S

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