MODELING AND CHARACTERIZATION OF PHOTOVARACTOR FOR MICROWAVE OPTOELECTRONICS

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ABSTRACT

Optical control of microwave circuits using photodiode junction capacitance variation due to optical illumination has some advantages such as simplicity and wide possibilities in application, high tuning range, accuracy, and speed. We have proposed to call as photovaractor the device which capacitance changes under illumination and which is used for optical control of microwave circuits. The numerical one-dimensional drift-diffusion model of the photovaractor based on the InP/InGaAs/InGaAsP heterostructure which is taking into account influence of the external electric circuit and parasitic elements was used to calculate the junction capacitance change under illumination. The experimental results and theoretical study of the photovaractor in the frequency range up to 3 GHz are presented.

I. INTRODUCTION

In recent years application of optoelectronic devices for optically controlled microwave circuits are widely discussed in literature. Optical control has some advantages in comparison with electrical control such as high tuning speed and range, good accuracy and isolation between controlling and microwave signals. Also in some applications, for example in the phased array antennas, usage of the optoelectronic devices with fiber-optic cables could considerably reduce size and weight of a system. In the last decade various radio frequency control functions, such as gain control of amplifiers, oscillator frequency tuning and modulation, oscillator injection locking and reference frequency distribution, microwave switching, phase shifting, and attenuation have been demonstrated using optical control, Galwas (1) and Nagra et al (2).

Application of photodiodes in optically controlled microwave circuits is rather perspective because of their low cost and simplicity in usage. One of the optical control techniques with the help of a photodiode is utilization of its capacitance-voltage characteristic nonlinearity caused by optical illumination. We proposed to call such device as photovaractor, Malyshev et al (3). It is necessary to note, that in usual linear regime the photodiode operates under reverse bias voltage, thus junction capacitance has a minimum value and practically does not change under illumination. In the linear regime the photodiode has maximal responsivity and bandwidth, and this regime is widely used in fiber-optic links. For effective optical control of microwave circuits it is necessary to use the nonlinear regime of the photodiode, which is achieved in bias free conditions. In this regime capacitance-voltage and current-voltage characteristics are changed by the optical power. Thus specially designed photodiode should be used for direct optical control of microwave circuits as photovaractor.

The main goal of this paper is theoretical and experimental study of the photovaractor capacitance behavior under various illumination powers. For this purpose the one-dimensional drift-diffusion model has been used to calculate the junction capacitance under different design parameters and working regimes of the photovaractor. The theoretical results are compared with measurement characteristics of the photovaractor.

II. MODEL OF THE PHOTOVARACTOR DIODE

The photovaractor described in this paper is the p-i-n photodiode with front illuminated p^+-region placed in the pigtailed fiber optical module. The p-i-n structure consists of the 0.8μm, $2\cdot10^{18}$cm^{-3} p-doped InGaAsP top layer, the 0.2μm, $1.2\cdot10^{15}$cm^{-3} undoped n-InGaAsP layer, the 2.5μm, $1.2\cdot10^{15}$cm^{-3} undoped n-InGaAs absorption layer, and the 400μm, $3\cdot10^{18}$cm^{-3} Te doped n^+-InP substrate, Malyshev et al (4). The cross section of the modeled structure and equivalent circuit of the photovaractor are shown in Fig. 1. Charge carrier transport in the photovaractor structure is described by the drift-diffusion model, Chizh and Malyshev (5). The total current I through the photodiode is the sum of conductivity and displacement currents:

$$I(t)=\frac{A}{d}\int_0^d\left(j_n(x,t)+j_p(x,t)-\varepsilon_0\varepsilon(x)\frac{\partial\varphi(x,t)}{\partial x\partial t}\right)dx\ . \qquad (2)$$

where A is photosensitive area of the photovaractor, d is the chip thickness, j_n and j_p are electron and hole current densities, φ is electrical potential. The relationship between the photovaractor voltage U and the total current I through the photovaractor is calculated from the equivalent circuit, which is described by the following equations:

$$\begin{cases} U(t)+R_S I(t)+L_P \dfrac{dI(t)}{dt}-U_{Cp}(t)=0 \\ RI_G(t)+L\dfrac{dI_G(t)}{dt}-V+U_{Cp}(t)=0 \\ I(t)+C_P\dfrac{dU_{Cp}(t)}{dt}+C\dfrac{dU_C(t)}{dt}-I_G(t)=0 \\ U_C(t)-U_{\mu W}(t)-U_{R_L}(t)-U_{Cp}(t)=0 \\ R_L C\dfrac{dU_C(t)}{dt}-U_{\mu W}(t)+U_{R_L}(t)=0 \end{cases} \tag{3}$$

where V is bias voltage, I_G is current through power supply, U_C is blocking capacitance voltage, U_{Cp} is parasitic capacitance voltage, $U_{\mu W} = U_o \sin\omega t$ is the incident sinusoidal microwave signal, U_{RL} is microwave signal reflected from the photodiode. For discretization of the set of equations (3) the finite difference method was applied. As a results of simulation the functions $U(t)$ and $I(t)$ are obtained. The S_{11} parameter of the photodiode, the junction capacitance Cj and resistance Rj are calculated from the following equations:

$$Cj=\frac{\Delta I\sin\Delta\varphi}{\omega\Delta U},\quad Rj=\frac{\Delta U}{\Delta I\cos\Delta\varphi},\quad S_{11}=\frac{\Delta U_{R_L}}{\Delta U_{\mu W}}e^{j\Delta\psi}, \tag{4}$$

where ΔI, ΔU are amplitudes, and $\Delta\varphi$ is phase shift between the sinusoidal part of the functions $I(t)$ and $U(t)$, ΔU_{RL}, $\Delta U_{\mu W}$ are amplitudes, and $\Delta\psi$ is phase shift between the sinusoidal part of the functions $U_{\mu W}(t)$ and $U_{RL}(t)$, j is imaginary unit.

III. RESULTS AND DISCUSSION

The results of the photovaractor capacitance behavior modeling under various bias voltages, illumination powers and frequencies are shown on Fig. 2 and Fig. 3. One can see from Fig. 2 that there is different capacitance behavior under illumination in the regions of low and high frequency. At the frequencies less than 1 GHz the capacitance change with optical power variation strongly depends on the frequency. It is connected with influence of the diffusion mechanism of charge carrier transport in p-i-n junction since the typical value of carrier transport time due to diffusion mechanism in such p-i-n structures is about $10^{-8}\div10^{-9}$ s. At frequencies higher than 1 GHz the drift mechanism with carrier transport time about $10^{-10}\div10^{-11}$ s dominates and capacitance change with optical power variation almost does not depend on the frequency.

Fig. 3 shows that photovaractor capacitance may be strongly modified by illumination power. It is necessary to note that photovaractor capacitance is tuned by optical power with high accuracy. So the usage of the nonlinear regime in bias free conditions gives us a possibility to obtain the effective photovaractor. Comparing Fig. 3a with Fig. 3b one can see that even the low reverse bias -0.25 V considerably reduces the capacitance variation and, consequently, the tuning range which determined by the capacitance ratio C_{max}/C_{min}. It can be explained that under the low reverse bias the working regime of the photovaractor becomes close to the linear one and therefore incident optical power weekly changes the photovaractor capacitance. Although in this case, using small reverse bias we could increase the tuning accuracy.

Fig. 4 shows the S_{11} parameters of the photovaractor measured in the frequency range from 15 MHz up to 3 GHz with 15 MHz step under unmodulated illumination power at the 1.55 μm wavelength from zero up to 3 mW and various bias voltages. The measurements have been carried out using HP 8753C Vector Network Analyzer. One can see from Fig. 4 that the S_{11} parameter considerably changes under illumination. However, even under the low reverse bias voltage -0.25 V (Fig. 4b) the S_{11} parameter change under illumination reduces comparing with the bias free condition (Fig. 4a). Fig. 5 shows the photovaractor capacitance versus illumination power under various frequencies and bias voltages. The capacitance was calculated from S_{11} parameters using the equivalent circuit of the photovaractor (Fig. 1b). Fig. 3 and Fig. 5 show a good correspondence between simulated and experimental characteristics.

IV. CONCLUSIONS

The model and characteristics of the photovaractor have been presented. Numerical simulation of the photovaractor using the drift-diffusion model describes the photovaractor capacitance behavior under various optical powers, bias voltages and frequencies and well corresponds to the experimental data. For efficient optical control it is necessary to use the nonlinear regime of the photovaractor, which is achieved in bias free conditions. The photovaractor diode can be effectively used in optically controlled broad band oscillators, phase shifters and bandpass filters as well as for the remote control of phased array antennas.

ACKNOWLEDGEMENT

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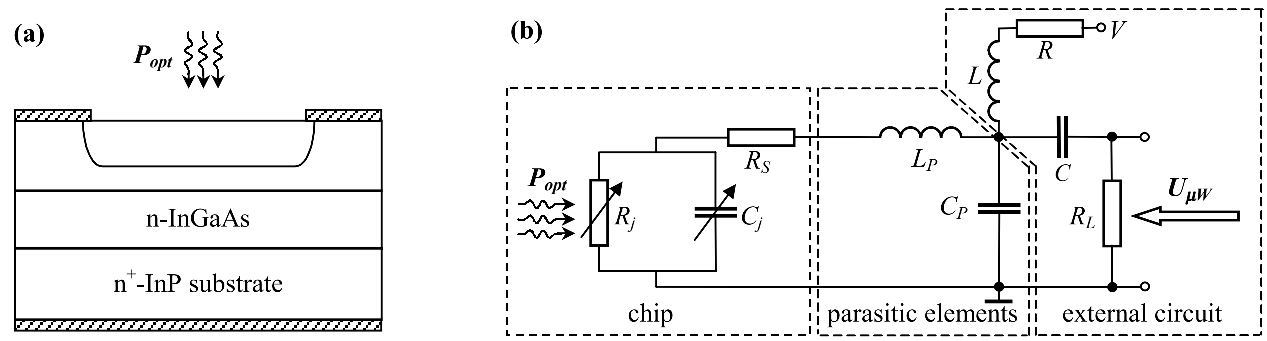

Fig. 1. Cross section of the photovaractor p-i-n structure (a). Equivalent circuit of the photovaractor (b). C_j, R_j are junction capacitance and resistance, R_S is series resistance, L_P, C_P are parasitic inductance and capacity, C, L are blocking capacitor and inductor, R is resistor of a power supply, and R_L is microwave load resistance.

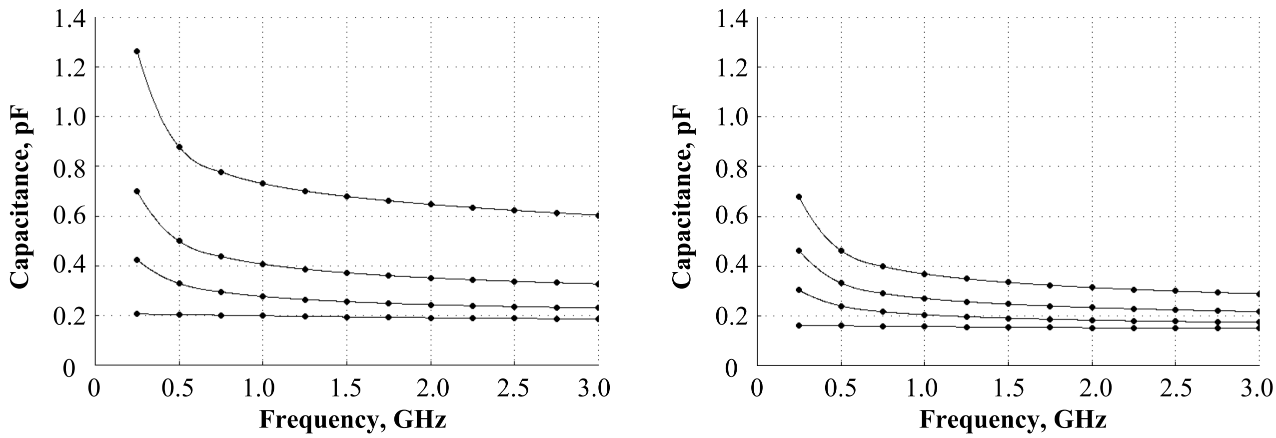

Fig. 2. Calculated photovaractor capacitance versus frequency under various illumination powers and bias voltages: (a) bias 0 V, and (b) bias -0.25 V (1 – 0 mW, 2 – 1.0 mW, 3 – 2.0 mW, 4 – 3.0 mW).

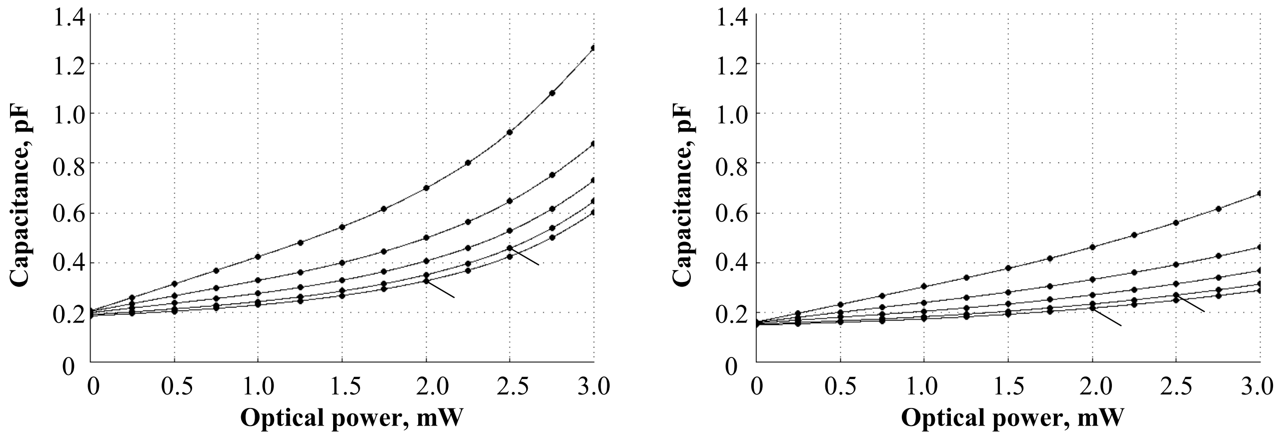

Fig. 3. Calculated photovaractor capacitance versus optical power under various frequencies and bias voltages: (a) bias 0 V, and (b) bias -0.25 V (1 – 0.25 GHz, 2 – 0.5 GHz, 3 – 1.0 GHz, 4 – 2.0 GHz, 5 – 3.0 GHz).

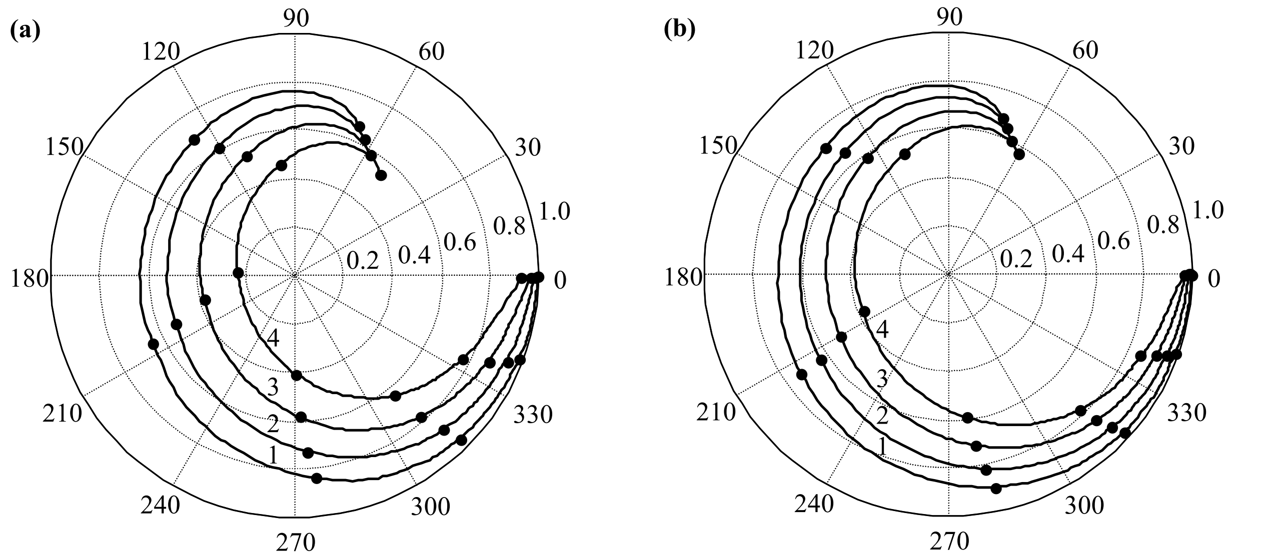

Fig. 4. Measured S_{11} parameter of the photovaractor under various bias voltages and illumination powers: (a) bias 0V, and (b) bias -0.25 V (1 – 0 mW, 2 – 1.0 mW, 3 – 2.0 mW, 4 – 3.0 mW). Markers indicate the frequency from 15 MHz to 3.0 GHz with 0.5 GHz step.

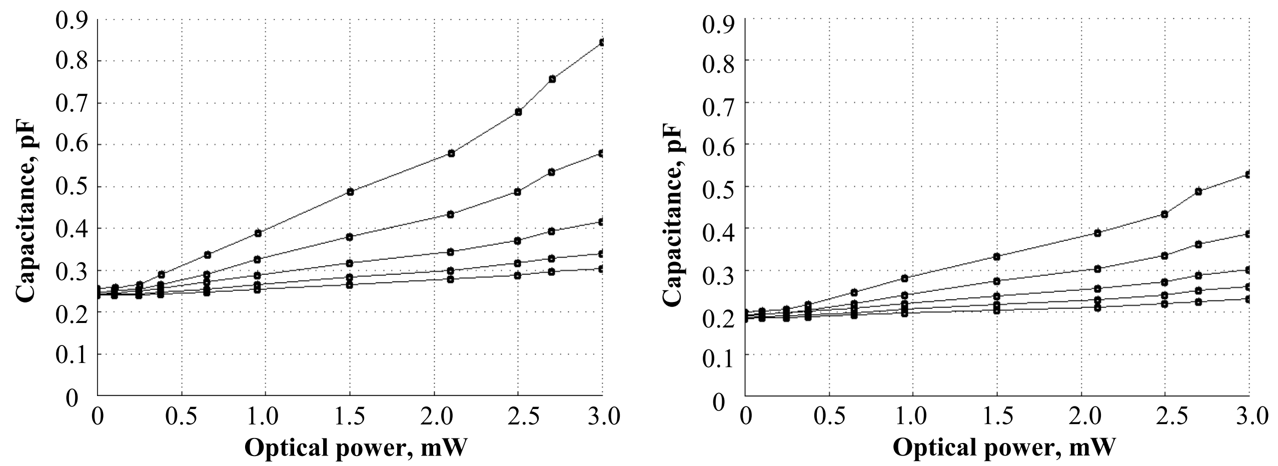

Fig. 5. Capacitance variation versus illumination power for various frequencies and bias voltages: (a) bias 0 V, and (b) -0.25 V (1 – 0.25 GHz, 2 – 0.5 GHz, 3 – 1.0 GHz, 4 – 2.0 GHz, 5 – 3.0 GHz).