Photovaractor for Remote Optical Control of Microwave Circuits

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***Abstract*—The photovaractor for remote optical control of microwave circuits was studied. The photovaractor was fabricated as a p-i-n photodiode placed in a pigtailed fiber optical module. The study of the impedance in the frequency range up to 3 GHz in darkness and under illumination has shown that the photovaractor capacitance strongly depends on the incident optical power. The capacitance variation of the photovaractor diode under illumination is discussed.**

***Index Terms*—Optical control, photovaractor, p-i-n photodiode.**

I. Introduction

In MICROWAVE circuits, the various varactor diodes are usually used for control of active devices. In recent years, the applications of optoelectronic devices for optical control in area of microwave photonics are widely discussed in literature [1]–[3]. The advantages of the optical control are high tuning speed and range, good accuracy, and isolation between controlling and microwave signals. Moreover, it gives the possibility of remote optical control by means of fiber-optic links, which is important for phase array antennas and fiber-optic microwave subcarrier systems.

One of the effective methods of optical control of microwave circuits is usage of nonlinear regime of the photodiode, which is achieved under bias free condition. In this regime, the capacitance–voltage and the current–voltage photodiode characteristics are changed under illumination. We have proposed to call such a device as photovaractor [4]. In the photodiode and photovaractor, the optical radiation should produce the maximum possible value of the photocarriers. But, in the photovaractor, the significant change of the impedance should be received in contrast to the photodiode where the maximum responsivity and bandwidth should be achieved. This is the main difference between the photovaractor and photodiode which determines their design and operating regime. It is necessary to note that if a sufficient reverse bias voltage is applied to the photovaractor, then it begins to operate in the linear regime like common photodiode, and its impedance practically does not change under illumination.

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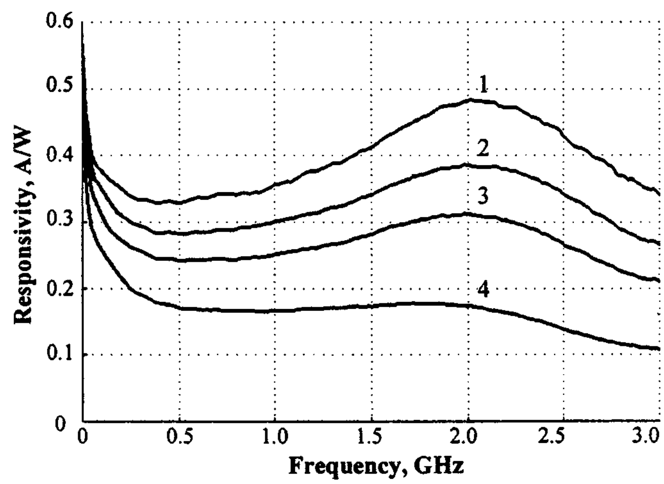


Fig. 1. Photovaractor responsivity for 1.3 μm wavelength versus frequency under various reverse bias voltages: 1—bias -5 V, 2—bias -2 V, 3—bias -1 V, 4—bias 0 V.

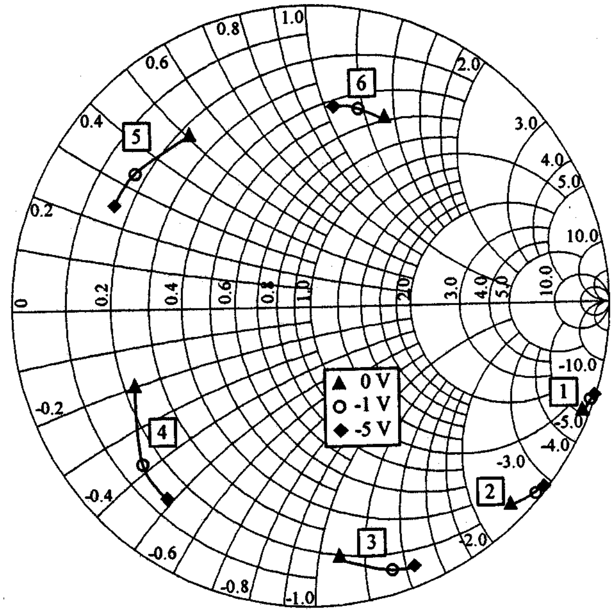
The main goal of this paper is experimental study of the photovaractor parameters' behavior under various bias voltages and illumination powers.

II. Photovaractor Diode

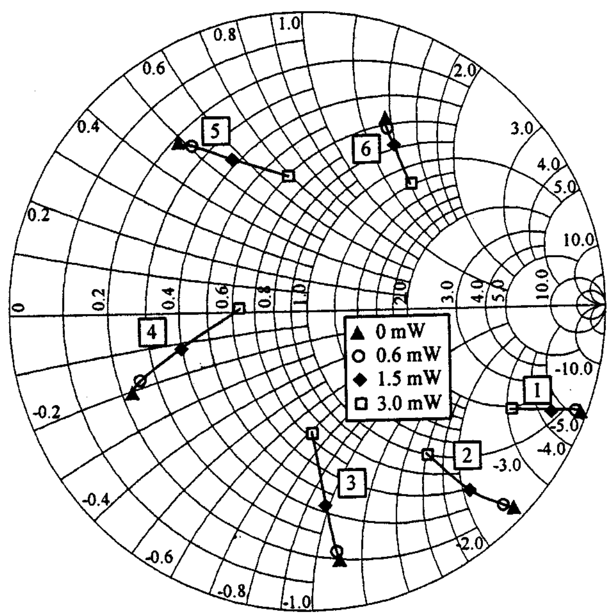
The photovaractor described in this paper is the p-i-n photodiode with front illuminated p^+-region placed in the pigtailed fiber optical module. To reduce reflection from the fiber–air and air–chip interfaces, the special matching medium, which has a refractive index close to that of quartz fiber, has been placed between the chip and fiber [5]. The photodiode has been fabricated into n^+-InP/n-InGaAs/n-InGaAsP heterostructure. The epitaxial layer is composed of 1.0 μm, $1.2 \cdot 10^{15}$ cm^{-3} undoped n-InGaAsP top layer, 2.5 μm, $1.2 \cdot 10^{15}$ cm^{-3} undoped n-InGaAs absorption layer, 400 μm, $3 \cdot 10^{18}$ cm^{-3} Te doped n^+-InP substrate. The p^+-region was formed by local diffusion of Zn into the wide band gap n-InGaAsP top layer. The diameter of the photosensitive area is 40 μm [6], [7].

Fig. 1 shows the measured photovaractor responsivity at the 1.3 μm wavelength versus frequency under various reverse bias voltages.

The photovaractor has wavelength range from 1.0 μm up to 1.65 μm. The measurements of the photovaractor characteristics have been carried out using HP 8753C Vector Network Analyzer.



(a)



(b)

Fig. 2. Change of the photovaractor impedance at the various frequencies (1—0.5 GHz, 2—1.0 GHz, 3—1.5 GHz, 4—2.0 GHz, 5—2.5 GHz, 6—3.0 GHz): (a) under variation of the reverse bias voltage in darkness, and (b) under zero bias voltage and variation of the illumination power.

III. Results and Discussion

The change of the photovaractor impedance at the various frequencies under variation of reverse bias voltage and unmodulated illumination power at the 1.3 μm wavelength is shown in Fig. 2.

Comparing Fig. 2(a) and (b), one can see that the impedance change under zero bias voltage and variation of the optical power is more significant than under variation of the reverse bias voltage in darkness.

To determine the junction capacitance variation from the reflection coefficient Γ the photovaractor equivalent circuit shown on Fig. 3 was used. Rj, Cj, Rs, Lp, Cp are junction resistance and capacitance, series resistance, parasitic inductance, and capacitance, respectively. The parasitic capacitance Cp is calculated from quasistatic capacitance–voltage measurements of the photovaractor diode in darkness. The parasitic inductance Lp and series resistance Rs were directly measured.

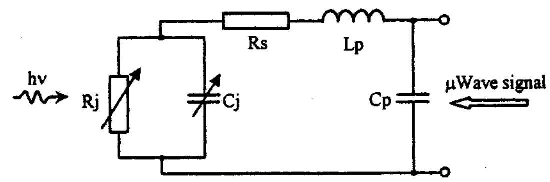
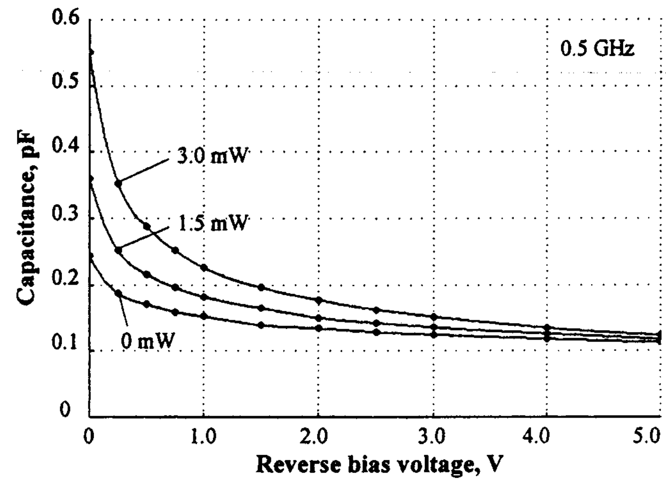
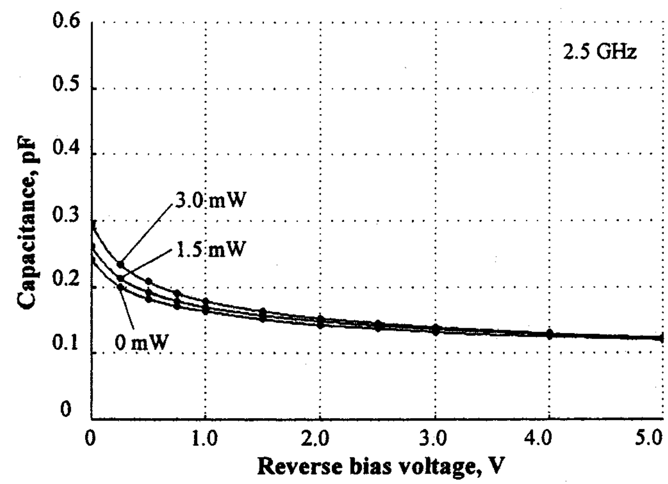


Fig. 3. Equivalent circuit of the photovaractor.



(a)



(b)

Fig. 4. Capacitance–voltage characteristics of the photovaractor under various optical powers and frequencies: (a) 0.5 GHz and (b) 2.5 GHz.

Fig. 4 shows the calculated from measured reflection coefficient capacitance–voltage characteristics in darkness and under illumination at the different frequencies. In Fig. 4, one can see that photovaractor capacitance can be strongly modified by illumination power. However, at the frequency 0.5 GHz [Fig. 4(a)], this change is more significant than at the frequency 2.5 GHz [Fig. 4(b)]. But in darkness, there is practically no capacitance change versus frequency. It is assumed that, at high frequencies, the generated photocarriers have no time to follow the change of

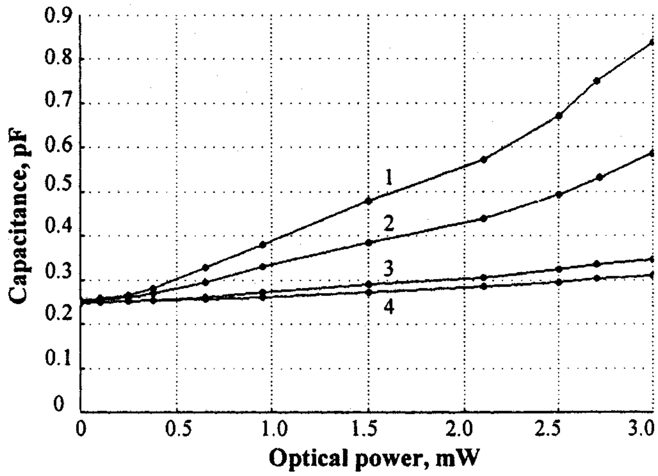


Fig. 5. Photovaractor capacitance versus optical power under zero bias voltage and various frequencies: 1—0.25 GHz, 2—0.5 GHz, 3—1.5 GHz, and 4—2.5 GHz.

the microwave signal. The operation of the photovaractor diode is based on the change of effective width of the space charge region under illumination. It is well known that p-i-n structure may be represent as a parallel plate capacitor [7]. Under the illumination, photocarriers, injected in between the plates, induce the charge on the plates, which modifies junction capacitance. There are the depleted region and space-charge neutrality region in the absorption layer. For the low frequencies, photocarriers generated both in the depleted region and space-charge neutrality region, modify the junction capacitance. The time required for the photocarriers to drift through the depleted region is less than the time required to diffuse through the space-charge neutrality region. Therefore, the only photocarriers generated in the depleted region, can modify the junction capacitance at the high frequencies.

The ratio $C_{\max}/C_{\min}$ depends on the variation of the optical power, the bias voltage, and frequency. For example, at the frequency 0.5 GHz and zero bias voltage the capacitance changes from $C_{\min} = 0.25$ pF to $C_{\max} = 0.55$ pF under the optical power variation from zero to 3.0 mW. In this case the ratio $C_{\max}/C_{\min}$ is equal to 2.2. At the reverse bias 5.0 V, and at the same frequency and variation of the illumination power, the capacitance ratio is only 1.1. At the frequency 2.5 GHz and zero bias voltage, the ratio $C_{\max}/C_{\min} = 1.2$, and at the reverse bias 5.0 V, the ratio $C_{\max}/C_{\min} = 1.0$. So, we can obtain an effective photovaractor using p-i-n photodiode, which can operate under bias free condition.

The photovaractor capacitance dependence on illumination power at different frequencies is shown in Fig. 5. One can see that the photovaractor capacitance is tuned by optical power with high accuracy. It is necessary to note that, for such photovaractor design at the frequencies less than 1 GHz, the capacitance strongly depends on the frequency. It is connected with influence of the diffusion mechanism of carrier transport, which is much slower than drift mechanism, on the junction capacitance recharge time. At frequencies higher than 1 GHz, the drift mechanism of carrier transport dominates and capacitance change with optical power variation almost does not depend on the frequency.

The photovaractor junction resistance strongly depends on the frequency. Under illumination the junction resistance decreases, but in this case, the resistance dependence versus frequency weakens. In any case, the photovaractor junction resistance under illumination is about units of kiloohms.

IV. Conclusion

The experimental characteristics of the photovaractor have been presented and discussed. The significant change of the photovaractor capacitance with the illumination power is achieved by operation under bias free condition where the capacitance–voltage-characteristic is highly nonlinear. Using such photovaractor and fiber-optic links, it is possible to realize the remote optical control of microwave circuits.

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