Regular paper

Photo-devices for optical controlling of microwave circuits

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Abstract — The most important optical devices which can be used for controlling microwave circuits will be presented in the paper. The performance and the parameters of the devices such as semiconductor microwave optoelectronic switches, photodiodes and phototransistors were described. The influence of the optical illumination on their microwave parameters will be described in details, including the our own investigations and simulations results. Several applications of such devices and their potential possibilities will be presented.

Keywords — microwave optoelectronic switch, photodiode, phototransistor.

1. Introduction

During last years it can be seen a new trend in the telecommunication field – merging the optical and the microwave techniques. It means that there is a need to drive the optical devices with the high frequency or microwave signals. On the other hand we need to control the microwave circuits by means of the optical signals. Such optically controlled microwave circuits are wanted for optically provided processing of microwave signals. They are strongly needed for new types of radar. Also the optically controlled microwave mixers and oscillators are used in hybrid-fibre radio applications [1].
One of the solutions for optical control of microwave circuits is the developing of the microwave devices with the capability of changing their microwave parameters such as capacitance, impedance, reflectance or current source value due to the absorption of the light. Microwave circuit designer usually can propose a circuit, with the use of such a device, which will have the possibility of changing its attenuation/gain, or generation frequency by means of the illuminating optical power. The various families of such devices will be described in the following sections of the paper.

2. Bulk photoconductive devices

2.1. Photoconductive effect

The most common application of the illuminated bulk semiconductor devices is switching. The idea is to use a piece of semiconductor material to make a gap in a microwave transmission line, and then the switch is activated by illumination. The principle of the operation relies on the light absorption in the semiconductor material. When the incident photon energy is higher than the band gap of the semiconductor, the photon is absorbed and the creation of electron-hole pair takes place. This phenomenon causes the increase of the carrier density in the semiconductor material under the optical illumination, and therefore the increase of the semiconductor conductivity. Light absorption coefficient α depends on the type of semiconductor and also on the light wavelength λ (Fig. 1):

$$\alpha\ [\mathrm{cm}^{-1}] = 2 \cdot 10^4 \sqrt{hf - E_g\ [\mathrm{eV}]}\,, \tag{1}$$

where h is the Planck's constant, f is a frequency of the incident light and E_g is a band gap energy of semiconductor material.

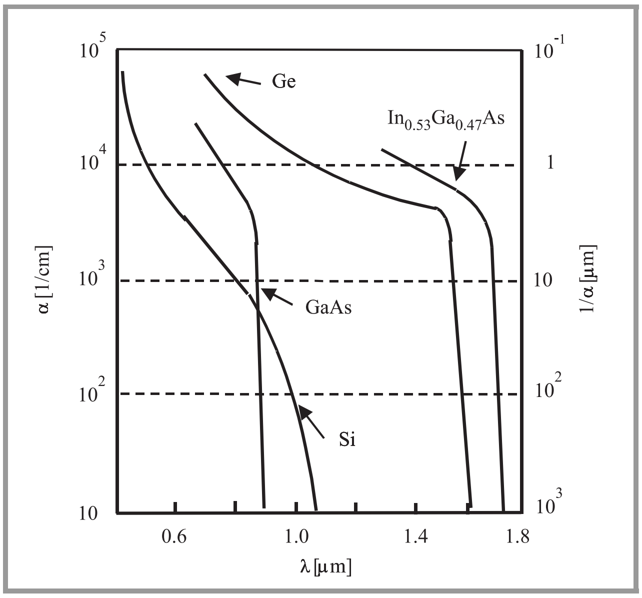

Fig. 1. Light absorption coefficient α and penetration depth $1/\alpha$ versus wavelength λ for different types of semiconductor material.

The absorption of an optical power P_0 in the semiconductor material can be described by the exponential law, as it is expressed by relation (2):

$$P_{abs} = P_0(1-\rho)\,(1-e^{-\alpha x})\,. \tag{2}$$

It is important to notice that the optical power penetrating the semiconductor material is lower than P_0 because some part ρ of the optical power is reflected from the semiconductor surface due to light refraction coefficient difference.

2.2. Photoconductive microwave switches

The basic construction and idea of the operation of the photoconductive microwave switch is shown in Fig. 2. The PC switches base on the transmission line, coplanar line or microstrip one, fabricated on semiconductor [2 – 4]. The conducting strip of the coplanar line has a gap causing the semiconductor to be exposed to the optical illumination.

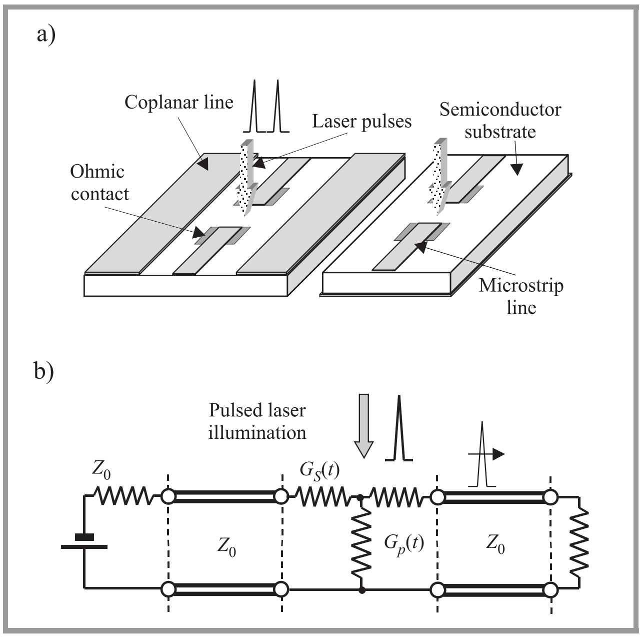

Fig. 2. Schematic illustration of a photoconductive microwave switch (a), and equivalent circuit (b).

When the light illuminates the gap area, such that its photon energy is greater than the semiconductor band gap, the light is absorbed and the free electron-hole pairs are generated. Thus, the conductivity of the semiconductor is altered. The illumination creates the surface plasma in the semiconductor. This surface plasma enhances the surface conductivity and bridges the gap in the strip conductor. Then the microwave signal can propagate through the switch.

In Fig. 2b the equivalent circuit of PC switch is shown. The values of the conductances series G_S and parallel G_P are the function of the optical power and are modulated by laser pulses.

Example: The typical parameters of a microstrip switch made on a silicon substrate are: refraction coefficient of semiconductor material $n_r = 3.6$, electron and holes mobilities $\mu_n + \mu_p = 2000$ cm^2·V^{-1}·s^{-1}, strip metalisation gap $L = 0.034$ cm, switching ON pulse energy $E_1 = 10$ μJ and $hf/e = 2.34$ V. Then the optically generated conductivity in the microstrip gap is equal to 5 S (it means 0.2 Ω). Thus in the ON state the optoelectronic microstrip switch has microwave reflection coefficient with magnitude equal to −54 dB and in the OFF state equal to −0.06 dB. They are good results.

The photoconductive microwave switches promise faster rise and fall time (typically in the picosecond range), broader bandwidth, ability to handle high power, and simplicity of operation in comparison to the conventional GaAs MESFET or PIN diode switches. Another advantage is the electrical isolation between the controlling optical signal and the gated microwave signal.

The very short electrical pulses generated with the use of the PC switches are used for measurements in the millimetre and sub-millimetre bands, and for the time domain measurements of the dielectric materials (Fig. 3), antennas, transistors and microwave amplifiers, especially if they work far from bands of the frequency domain network analysers.

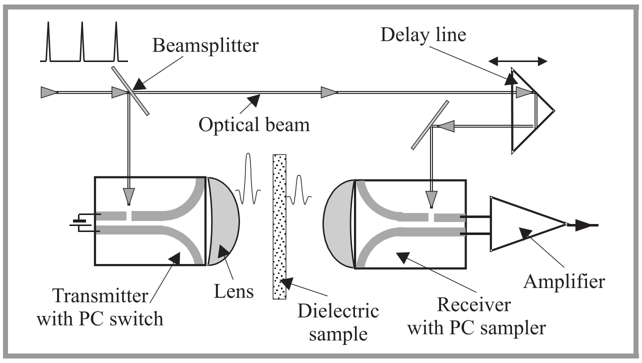

Fig. 3. Configuration of the system for transmission measurements of the dielectric properties of materials in the millimetre-wave region.

There was some investigations of the use of the variable impedance provided by an open-ended microstrip line fabricated on the silicon substrate – described in [5, 6]. However, the use of such a device in the oscillator tuning circuit gives not enough good performance.

3. PIN photodiodes

3.1. PIN photodiode performance

The commonly used microwave semiconductor devices with possibility of the optical control are photodiodes – especially PIN type ones, and phototransistors.

A PIN photodiode is a semiconductor junction device consisting of *p*-type and *n*-type semiconductor regions separated by an intrinsic layer (*i*) (Fig. 4a). In normal mode of operation a reverse-bias voltage applied across the device is large enough to make the intrinsic region fully depleted of carriers. An electric field resulting from reverse bias is equal to the saturation field. It means that during most of the transit the carriers travel at the saturation velocity.

When the light illuminates the semiconductor and the photons have its energy equal to or greater than the semiconductor band gap the generation of free electron-hole pairs takes place. The high electric field present in the depletion region separates the photocarriers. As the carriers traverse the depletion region, the current flow is induced. It means that in the equivalent circuit of PIN photodiode the optical illumination effect can be model by current source [7].

The performance of a photodiode is often characterised by the responsivity R. The photodiode responsivity is a ratio of generated photocurrent I_{ph} to the optical illumination power P_{opt}:

$$R = \frac{I_{ph}}{P_{opt}} \qquad (3)$$

and is expressed in A/W.

The responsivity can be expressed also with the use of internal quantum efficiency η:

$$R = \frac{\eta q}{hf}. \qquad (4)$$

The internal quantum efficiency is the number of electron-hole pairs generated per incident photon of energy equal to hf. The typical values of commercially available PIN photodiodes are equal to about 0.8 A/W.

The optical illumination causes the change in the junction parameters and thereby changes the microwave scattering parameters S_{11} of the photodiode. Expect the photodetection, this effect can be used to perform an optical and a microwave signals mixing. Also the optical control of a microwave circuit containing the PIN photodiode can be done in this way. The examples of S_{11} measurements in the case of optical illumination are shown in Fig. 5.

The impedance changes of typical PIN photodiode under the optical illumination are relatively small and sometimes not sufficient to use in some microwave circuits applications [8, 9]. Therefore there are other ways to improve the possibility of the microwave circuit control by means of the optical illumination and with the use of the photodiodes. It is worth to point an approach using the photodiode set to work with a varactor diode [8]. This approach is used in the microwave phase shifters [8, 10].

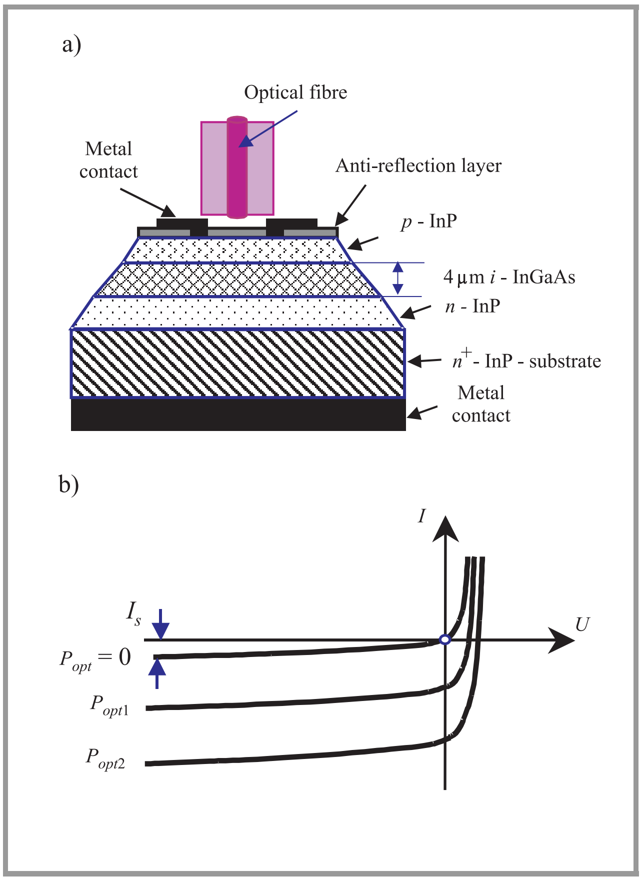

Fig. 4. PIN photodiode: (a) schematic cross-section of PIN photodiode; (b) diode characteristics $I(U)$ for different optical power.

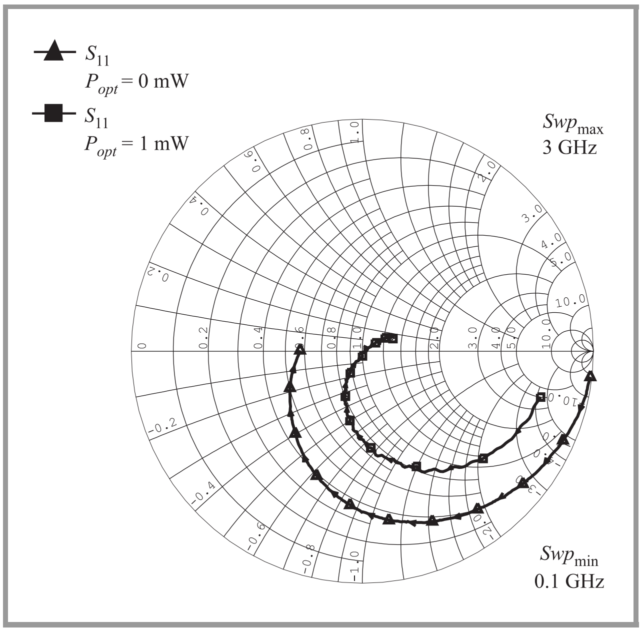

Fig. 5. Example of microwave reflectance of PIN photodiode under optical illumination.

3.2. Microwave parameters of PIN photodiode

A microwave behaviour of the PIN photodiode can be described by means of, either the scattering parameters, or the equivalent circuit/model. To determine the PIN photodiode equivalent circuit from the measurements, the special

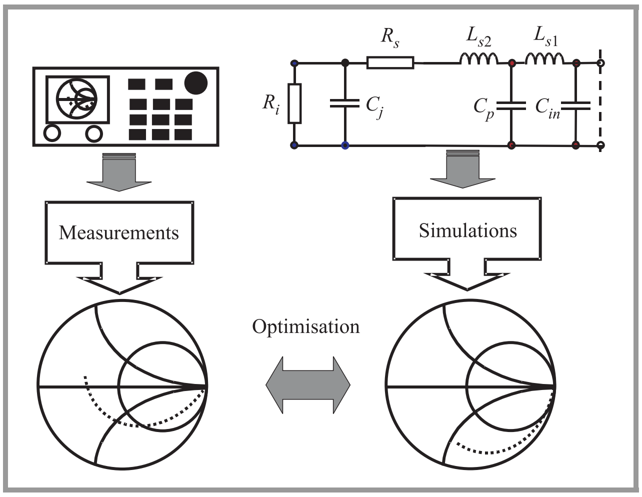

Fig. 6. Illustration of equivalent circuit extraction method from the measurements.

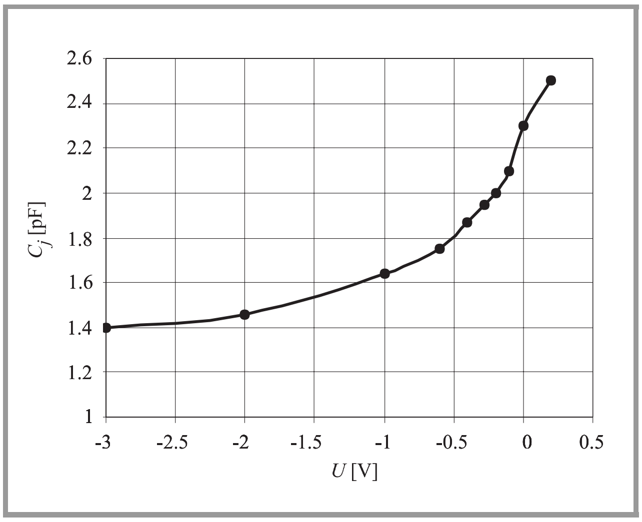

Fig. 7. Extracted PIN junction capacitance versus bias voltage characteristic.

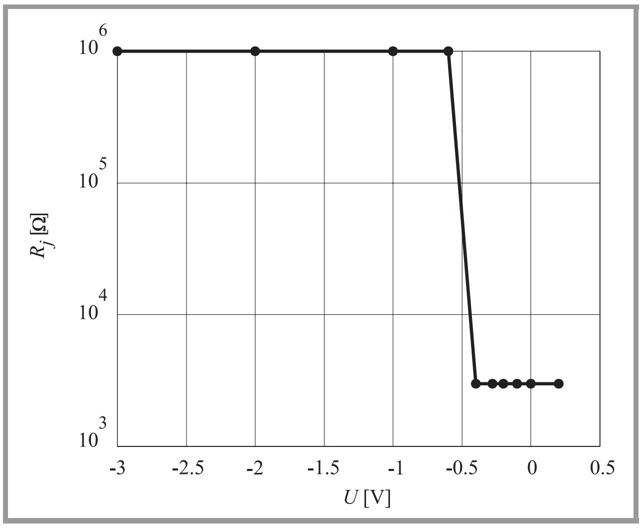

Fig. 8. Extracted PIN junction resistance versus bias voltage characteristic.

method of extraction was used. This method contains three steps:

a) measurements of the photodiode reflection coefficient Γ_{meas} within a defined frequency range, and at different bias voltages;

b) assumption of the equivalent circuit scheme, i.e. defining the R, L, C elements being contained;

c) the use of the special microwave simulating software (in our case *Microwave Office*) to calculate Γ_{sim}.

After these steps the final part of the extraction can be made. It is the optimisation of the variable values of the equivalent circuit elements to achieve fitting the simulation results to the measurements (Fig. 6). When matching is impossible, then the equivalent circuit is modified. The good matching, obtained within the specified frequency range, and at specified bias voltage, gives the values of the model parameters for these frequencies and at this voltage.

An example of PIN photodiode model extracted from the S_{11} measurements is shown below. The values of the parasitic elements are: $C_p = 0.03$ pF, $C_{in} = 0.4$ pF, $L_{s1} = 3$ nH, $L_{s2} = 4.1$ nH. The value of junction series resistance was found to be approximately constant and equal to $R_s = 29\ \Omega$. The extraction procedure repeated for different bias voltages gives the photodiode voltage characteristics (see Figs. 7 and 8).

4. Photovaractor

A type of semiconductor diodes very commonly used in the microwave circuits is a varactor diode. However, traditional varactor diode is the device that has the junction capacitance with possibility of steering by means of the bias voltage applied across the device. The semiconductor structure of the varactor is specially designed to obtain relatively high range of the capacitance changes while biasing at different voltages. A new approach to the problem of changing the capacitance in the microwave device or circuit is the use of the optical illumination. The photovaractor is the new special kind of the semiconductor PIN diode that has possibility of steering the junction capacitance with the use of the optical power [11]. The photovaractor structure is specially designed to obtain the capacitance changes as high as possible while illuminating with the optical power. A typical photovaractor diode is a heterostructure type device. An example of the photovaractor cross-section is shown in Fig. 9.

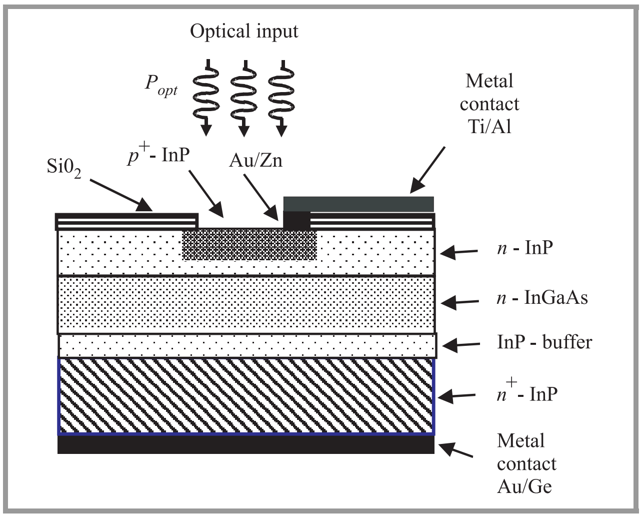

Fig. 9. Example of n-InP/n-InGaAs/n^+-InP photovaractor cross-section [7].

The maximal value of the photovaractor capacitance change under the optical illumination occurs at the bias around 0 V. For example, at the bias voltage equal to +0.1 V the capacitance changes from $C_{\min} = 2.75$ pF up to $C_{\max} = 69$ pF, under the optical power variation from 0 up

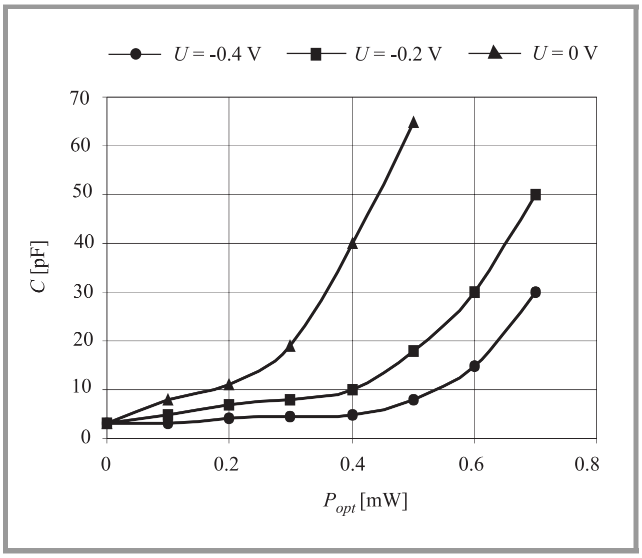

Fig. 10. Measured photovaractor capacitance versus optical power characteristics at different bias voltages.

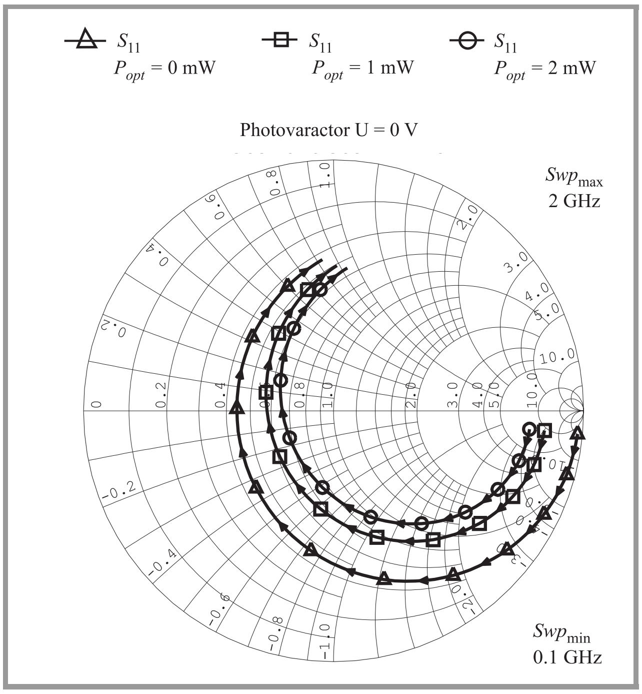

Fig. 11. Example of microwave reflectance S_{11} of PIN photovaractor under optical illumination.

to 0.4 mW. Then the ratio $C_{\max}/C_{\min}$ is equal to 25. An example of the photovaractor measured capacitance versus the optical power characteristics at different bias voltages is shown in Fig. 10.

However, the highest value of capacitance changes can be noticed for the capacitance measured at the several hundreds of MHz. The capacitance measured or extracted at the higher frequencies, for example few GHz, has smaller values because of fact that at high frequencies the generated photocarriers have no time to follow the change of a microwave signal. Nevertheless, the photovaractor capacitance at the microwave frequencies can be sufficient to provide the optical control of various microwave circuits, especially the oscillators (Fig. 11) [12, 13].

5. Optically variable capacitor

5.1. Photodiode-varactor couple

An optically variable capacitor (OVC) is new type of microwave-optical device. This device is the connection of the photodiode and the varactor diode. The photodiode is placed with a proper bias circuit, which allows to change the bias voltage across the varactor by means of the optical power illuminating the photodiode. The change of the bias voltage causes the change of the varactor capacitance, thereby allowing optical control of the circuit containing the varactor (Fig. 12). The problem of the connection can be solved in different ways, and two of the solutions are specially interesting.

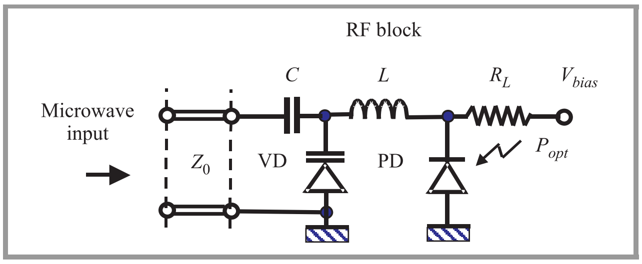

Fig. 12. Photodiode-varactor couple as a microwave optically variable capacitor.

The maximum of the optical power illuminating the photodiode corresponds to minimum of bias voltage across the varactor.

Example of microwave performance of the OVC is shown in Fig. 13. There is presented the OVC reflection coefficient S_{11} for different values of the optical power from 0 to 3 mW at the frequency equal to 1 GHz.

This type of the OVC circuit has the following features:

- RF block inductance keeps photodiode out of microwave signal;
- reverse biased varactor dissipates very little power;
- optical power required for control depends on the resistor used in the bias circuit, and can be relatively small;
- optical and microwave functions are performed in separate devices and they can be independently optimised;
- varactor diode used in this OVC can be assort with respect to highest capacitance changes ratio.

This type of circuit was developed to investigate the possibility of obtain an optically controlled microwave device for special microwave phase shifters and modulators [8, 10].

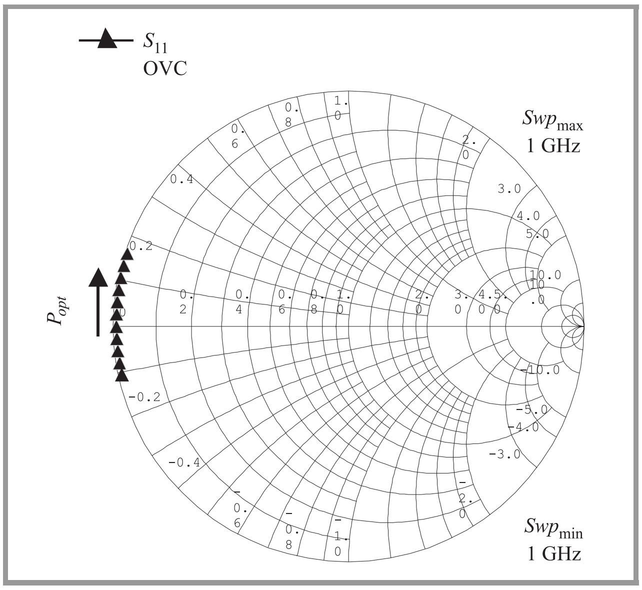

Fig. 13. OVC reflection coefficient S_{11} for different values of the optical power from 0 to 3 mW at the frequency equal to 1 GHz.

5.2. Optically variable capacitor with self-bias

Another very interesting solution is the device shown in Fig. 14. This device is the connection of photovoltaic cell with the varactor diode. The optical illumination of photovoltaic cell array causes photocurrent generation and then this current converted into the voltage is used to bias the varactor. In this manner the optical control of the varactor capacitance is provided. It is important to notice that this OVC is a bias-free device [14].

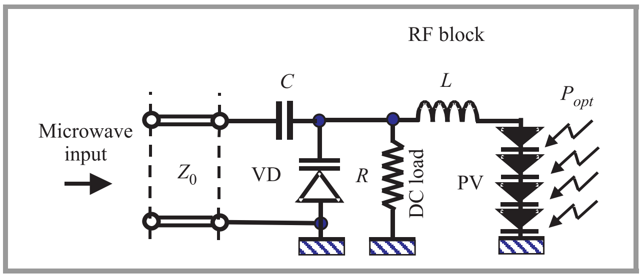

Fig. 14. Schematic idea of optically variable capacitor with self-bias using photovoltaic cell.

This OVC structure offers several advantages:

- RF block inductance keeps PV array out of microwave signal;
- reverse biased varactor dissipates very little power;
- optical power required for control is small;
- optical and microwave functions are performed in separate devices and they can be independently optimised;
- varactor diode is designed to produce desired capacitance swing with lowest possible RF insertion loss;

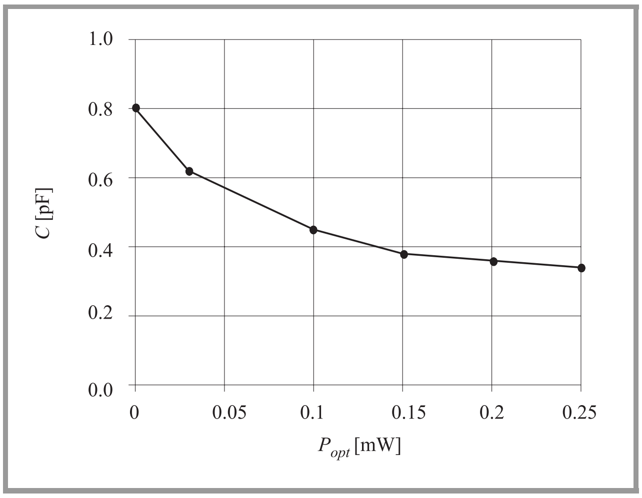

Fig. 15. Example of OVC performance: varactor capacitance versus optical power.

- photovoltaic call array is designed to generate desired output voltage range using the smallest optical power.

The comparison of two solutions described in this Section allows to conclude that the solution with the PIN photodiode provides faster change of the varactor capacitance, because the working bandwidth of the photovoltaic cells is usually small (Fig. 15).

6. Phototransistors

6.1. General types of phototransistors

The transistors are the types of semiconductor devices sensitive on the optical illumination. There are three types of microwave transistors: MESFET, HEMT and HBT [15 – 17]. Their main application is the photodetection. As the photodetectors transistors offer several advantages:

- detected signal is amplified by the device transconductance;
- in the case of HEMT the improvement of output signal to noise ratio;
- possibility of use of semiconductor materials with high electron mobility – like AlGaAs, InGaAs, InGaAsP to form the heterostructures in HEMT transistors; the energy gap in these materials can be chosen to obtain maximal sensitivity for given light wavelength;
- possibility of integration with other optoelectronic devices (even planar optics).

Generally, the optical illumination of the transistor causes the change of its parameters. This phenomenon, beside photodetection, can be used for mixing of the microwave and the optical signals. Because the optical illumination changes the microwave scattering parameters (S matrix) of the transistor then it is possible to optically control the microwave oscillator containing this device. Typical structures of microwave transistors MESFET, and HBT were shown in Figs. 16 and 17 [15, 16].

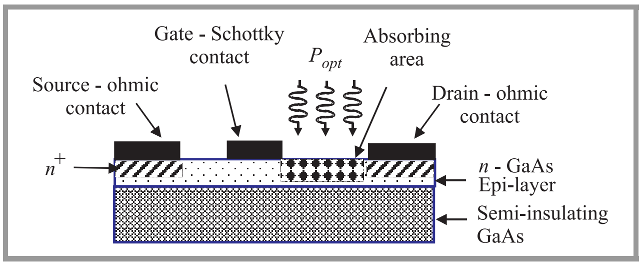

Fig. 16. Schematic cross-section of typical MESFET GaAs phototransistor structure.

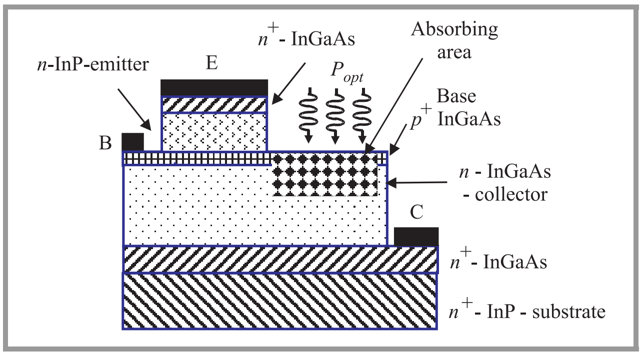

Fig. 17. Typical structure of HBT phototransistor.

From the technological point of view, the phototransistor structures are similar to the classical transistor structures. Nevertheless, there are two general requirements to fulfil. First, the light reflection at the transistor surface has to be as small as possible with the good transmission at the same time. Second, the light absorption has to be very high in the semiconductor layer chosen for this purpose. It is the channel area in the FET type transistors and the base-collector junction in case of bipolar junction transistors (BJT).
Generally the optical illumination of a semiconductor material causes the free electron-hole generation process. In the case of FET transistors this process increases the concentration of the minority carriers, for example, the holes in a n-type channel. Mathematically, Δp is expressed as:

$$\Delta p = \frac{\tau}{d} \cdot \frac{P_{opt}\lambda}{hc} \cdot \left[1 - \exp(-\alpha d)\right], \tag{5}$$

where P_{opt} is an incident optical power per unit area, d is a thickness of the active layer, τ is a minority carrier lifetime and c is the speed of light in vacuum.
The consequence of the excess holes concentration is the light-induced voltage V_{lit} at the Schottky gate:

$$V_{lit} = \frac{kT}{q} \ln\left[\frac{p + \Delta p}{p}\right], \tag{6}$$

where T is a temperature in Kelvins and q is an electron charge.
Hence, the illumination of the gate region has the same effect as forward biasing the gate.
The optical performance of phototransistors is also characterised by the responsivity R, which is expressed as

$$R = \frac{I_p}{P_{opt}}, \tag{7}$$

where I_p is the drain current under the illumination with the power P_{opt}.
The example of drain-source current I_{DS} versus drain-source voltage U_{DS} characteristics at different values of gate-source voltage U_{GS} and the illumination power is shown in Fig. 18.
In the case of bipolar transistors BJT the simplified modelling is used very often. These models are based on the assumption that the structure of a transistor, for example HBT, is configured to obtain maximal absorption of the light in the area of the base-collector junction.
Because in the active mode of operation the base-collector junction is reverse biased and the absorption of light takes place mainly in the junction depletion layer, the photocurrent flow is generated. Thus, the optical illumination of the transistor can be modelled with the use of additional

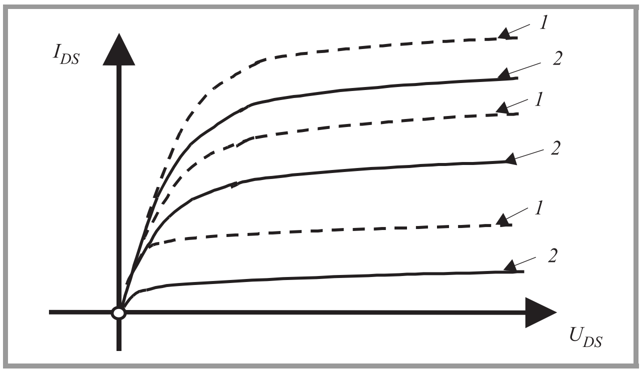

Fig. 18. Example of drain-source current I_{DS} versus drain-source voltage U_{DS} characteristics for HEMT with (*1*), and without (*2*) optical illumination.

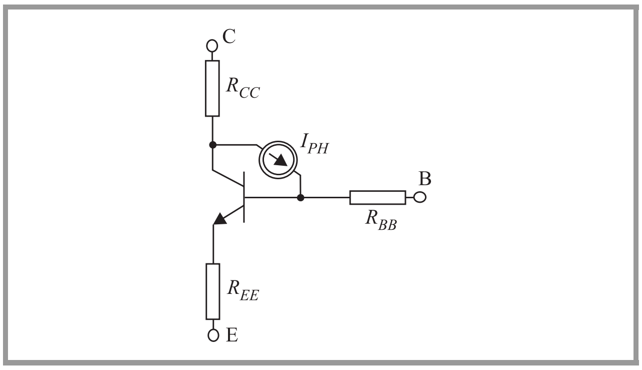

Fig. 19. Simplified SPICE-based HBT phototransistor model.

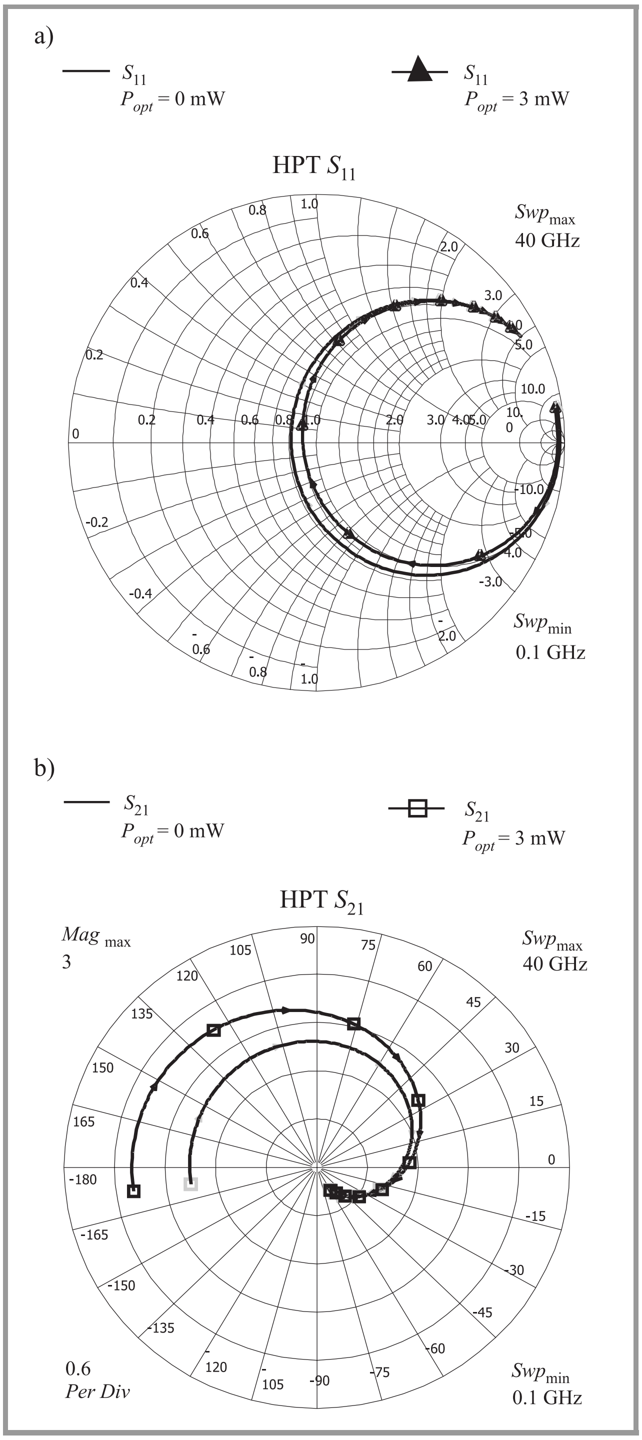

Fig. 20. Scattering parameters S_{11} (a) and S_{21} (b) characteristics respectively for 0 mW, and 3.0 mW of optical illumination.

current source connected between the base and the collector terminals. The value of photocurrent depends on the detection quantum efficiency of the base-collector junction. The quantum efficiency can be improved by increasing of the junction (depletion layer) thickness. On the other hand the light penetration depth in the semiconductor material should be approximately equal to the thickness of the base and collector layers.

6.2. Simulation of HBT phototransistor performance

The phototransistor parameters without illumination can be described with the use of standard modelling – for example the SPICE type parameters. There are other models available in the special simulating microwave software, for example Gummel-Poon. Then the additional current source can be used to consider the illumination influence (Fig. 19).

Such an improved model allowed to simulate the microwave scattering parameters of the phototransistor configured in common emitter. The knowledge of the HPT *S*-parameters microwave performance allows to design the microwave circuits – such an oscillator, or a mixer – containing the HPT device.

The examples of HBT phototransistor behaviour under the optical illumination are shown in Fig. 20. There are shown the scattering parameters S_{11}, S_{21} for the collector-emitter bias $U_{CE} = 2$ V and the base-emitter bias $U_{BE} = 0.77$ V, and the frequency band from 0.1 to 40 GHz.

All the *S*-parameters of the phototransistor depend on the optical illumination. Hence, there is possibility of use of the phototransistor as an optically controlled active device in the microwave oscillators, mixers and amplifiers [1, 15 – 17].

7. Conclusions

In many applications there is a need to control the microwave circuits performance and parameters by means of the optical illumination. For purposes of such a problem the photodevices which detect the optical signals and work in the optical receivers can be used. There are the PIN photodiodes and the phototransistors in this group of the devices. On the other hand the new types of the devices were developed, such as photoconductive switches, photovaractors or optically variable capacitors. These devices can be used in many different microwave circuits such oscillators, phase shifters, attenuators or ultra-short electrical pulse sources. There are many devices, which have relatively good performance. However, there are some problems, which are not overcome yet. The main problem of all microwave photonic devices is to achieve very large microwave bandwidth, with high optical quantum efficiency simultaneously. The next generations of the devices show the growing development in this field.

Acknowledgements

This work was supported by the State Committee for Scientific Research under contract no. 8T11D04214.

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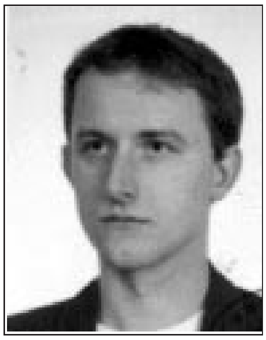

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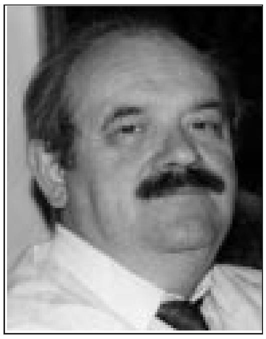

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