InGaAs p-i-n Photodiodes for Microwave Applications

Sergei Malyshev, Alexander Chizh, and Vatslav Andrievski

Institute of Electronics of National Academy of Sciences of Belarus, Laboratory of Semiconductor Optoelectronics,
22 Logoiski trakt, 220090 Minsk, Belarus, phone: +375-17-2812213, e-mails: malyshev@ieee.org, chizh@ieee.org

Abstract — **The experimental and theoretical study of the surface-illuminated InGaAs p-i-n photodiodes for such microwave applications as photonic microwave generation, optical control of microwave circuits and optoelectronic mixing is presented.**

I. INTRODUCTION

High-speed p-i-n photodiodes are used in the wide range of microwave photonics applications from fiber-optic lines and fiber-on-radio systems to photonic measurement systems for detection and conversion of optical signals [1], microwave generation [2-4], as well as optical control of microwave circuits and devices [5]. From microwave point of view the photodiode can be used as microwave generator, varactor, or mixer depending on its application in microwave system.

The main goal of this paper is provide some design optimizations of the surface-illuminated InGaAs p-i-n photodiodes for such microwave applications as photonic microwave generation, optical control of microwave circuits and optoelectronic mixing via measured data and computer modeling based on harmonic balance method [6] and one-dimensional drift-diffusion scheme [7].

II. P-I-N PHOTODIODE FOR MICROWAVE GENERATION

Recent advancements in microwave photonic systems have focused on high-power photodetectors. In microwave photonic systems using optical-fiber amplifier as a preamplifier high-power photodetectors can produce output electrical signal with enough power to directly drive the following microwave circuit [2,3]. The usage of high-power photodetectors increases the dynamic range and reduces the loss and noise figure of analogue fiber-optic links. Also photodetectors with high saturation current are needed for photonic measurement systems of high-speed electronic devices [4].

The p-i-n photodiode output power is limited by photocurrent saturation under high optical power due to screening of an internal electric field by photogenerated charge carriers (space-charge effect) and by thermal failure. So the key point in the design of high saturation current surface-illuminated p-i-n photodiodes is creation of strong internal electric field at the bias voltages near zero. It is known that high saturation current of the p-i-n photodiodes is associated with uniform and p-side illumination of photosensitive area, as well as low doping densities of absorption i-layer [8]. Fig.1 demonstrates the space-charge effect for p-side-illuminated p-i-n photodiode with 1μm-thick, 10^{18}cm^{-3} doped p$^+$-InP top layer, 1μm-thick, 10^{15}cm^{-3} doped n-In$_{0.53}$Ga$_{0.47}$As absorption layer and $3 \cdot 10^{18}$cm^{-3} doped n$^+$-InP substrate. It is seen that under illuminated power density 50W/cm^2 the electric field in the absorption n-InGaAs layer is completely destroyed.

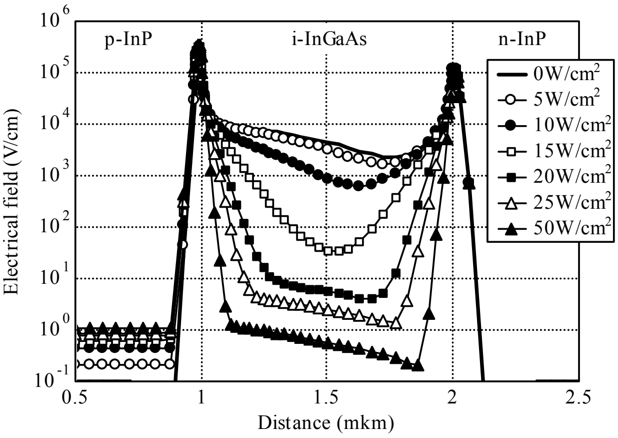

Fig.1. Simulated electric field into the p-i-n photodiode structure for different illuminated power densities at the wavelength 1.55μm and zero bias voltage.

Additional way to enhance the saturation current of the surface-illuminated p-i-n photodiode is to eliminate the influence of valance band discontinuity at the heterointerface p$^+$-InP/n-InGaAs on charge carriers transport. For this purpose it is possible to increase p$^+$-region doping density. This results in increasing of the electric field at the heterointerface p$^+$-InP/n-InGaAs, although in dark conditions the electric field in the absorption n-InGaAs layer remains the same. Thus, under illumination photogenerated holes can easier overcome the barrier at the heterointerface p$^+$-InP/n-InGaAs. Fig.2 shows the electric field in the studied p-i-n photodiode structure with different doping densities of the p$^+$-InP top layer for illuminated power density 50W/cm^2 and zero bias. It is seen that high doping densities of p$^+$-region results in the lowering of the space-charge effect.

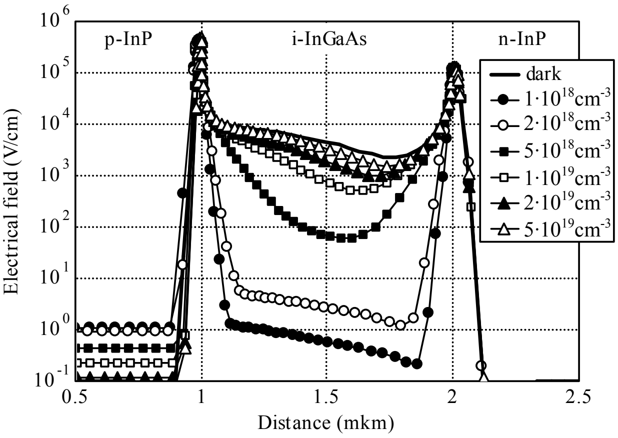

Fig.2. Simulated electric field into the p-i-n photodiode under different p$^+$-region doping densities for zero bias voltage and illuminated power density 50W/cm^2 at the wavelength 1.55μm.

Direct way to decrease the barrier for holes at the heterointerface p$^+$-InP/n-InGaAs and thus enhance saturation current is to use p$^+$-In$_x$Ga$_{1-x}$As$_{1-y}$P$_y$ top layer with narrower bandgap than InP. Fig.3 shows the electrical filed in the considered p-i-n photodiode structure with different composition of the p$^+$-In$_x$Ga$_{1-x}$As$_{1-y}$P$_y$ top layer for illuminated power density 500W/cm^2 and zero bias. One can see that usage of p$^+$-In$_{0.77}$Ga$_{0.23}$As$_{0.5}$P$_{0.5}$ top layer increases the optical power range more than order, because the barrier at the heterointerface p$^+$-InGaAsP/n-InGaAs is lower in two times than for the heterointerface p$^+$-InP/n-InGaAs. It is necessary to note that in this case p-i-n photodiode sensitivity is decreased at the shortwave region. To eliminate this effect and simultaneously remove the barrier at the heterointerface the thin graded bandgap n-In$_x$Ga$_{1-x}$As$_{1-y}$P$_y$ layer between p$^+$-InP top layer and absorption n-InGaAs layer can be used.

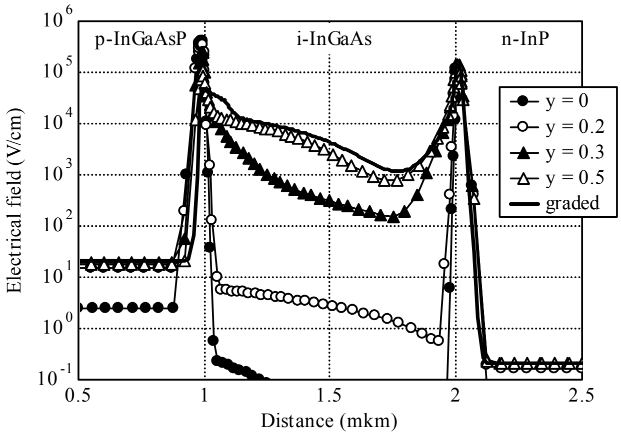

Fig.3. Simulated electric field into the p-i-n photodiode with different composition of the p$^+$-In$_x$Ga$_{1-x}$As$_{1-y}$P$_y$ top layer lattice-matched to InP for illuminated power density 500W/cm^2 at the wavelength 1.55μm and zero bias.

III.P-I-N PHOTODIODE FOR OPTICAL CONTROL

P-i-n photodiodes are of considerable interest in such microwave application as optical control of microwave circuits [5]. Optical control provides high tuning speed and range, easy integration with optical processing devices, as well as it is no matching and parasitic component problems since control signal is introduced directly to the microwave circuit. 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 is the usage of p-n junction capacitance change under illumination due to space-charge effect. Such p-i-n photodiode can be called as photovaractor [9]. In this application the main requirements to the photodiode are high capacitance ratio and low control optical power.

The photovaractor studied is 35μm-diameter p-side illuminated p-i-n photodiode placed in a pigtailed fiber optical module. Its epitaxial structure consisted of 1μm-thick, 10^{15}cm^{-3} undoped n-In$_{0.9}$Ga$_{0.1}$As$_{0.23}$P$_{0.77}$ top layer, 3μm-thick, 10^{15}cm^{-3} undoped n-In$_{0.53}$Ga$_{0.47}$As absorption layer, 1μm-thick, $3 \cdot 10^{18}$cm^{-3} doped n$^+$-In$_{0.9}$Ga$_{0.1}$As$_{0.23}$P$_{0.77}$ contact layer, and a 400μm-thick semi-insulating InP substrate. The p$^+$-region was formed by local Zn diffusion into the wide-bandgap n-InGaAsP top layer. Fig.4 shows the change of the photovaractor impedance under illumination with optical power from 0 to 4mW for different frequencies and zero bias voltage.

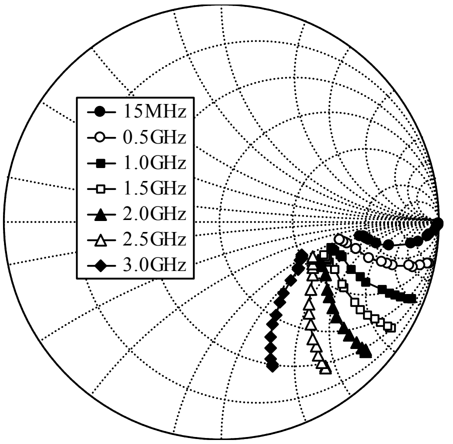

Fig.4. Photovaractor S_{11} parameters versus optical power at the wavelength 1.55μm under different frequencies and zero bias.

Fig.5 shows photovaractor p-n junction capacitance and resistance calculated from measured S_{11} parameters. One can see that for the frequencies lower than 0.5GHz p-n junction capacitance under illumination strongly depends on frequency and for the frequencies higher than 1GHz it is almost not depended on frequency and maximal capacitance ratio is about 2. Such capacitance behavior is explained by the fact that p-n junction capacitance consists of barrier capacitance, which increases under illumination due to decrease of space-charge region width and doesn't depend on frequency, and diffusion capacitance, which increases under illumination due to diffusion of nonequilibrium photogenerated charge carriers into the p- and n- sides of the p-n junction and strongly decreases at the high frequencies.

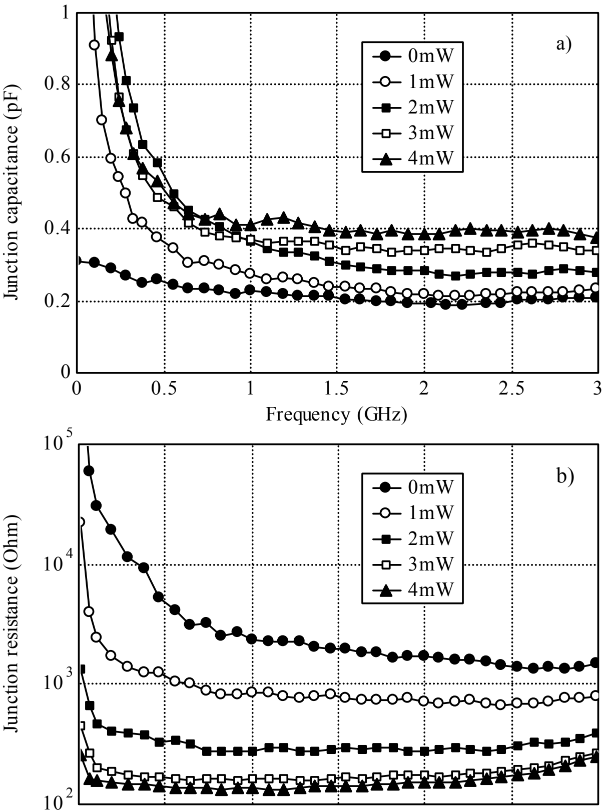

Fig.5. Photovaractor p-n junction capacitance (a) and resistance (b) versus frequency under different optical powers at the wavelength 1.55μm and zero bias voltage.

P-n junction resistance is significantly decreased by illuminated power as shown in Fig.5(b). However, for the illuminated power lower than 2mW p-n junction resistance is well above of typical microwave transmission line impedance 50 Ω and photovaractor impedance is determined only by p-n junction capacitance.

In the photovaractor design there are tradeoffs between high capacitance ratio, low control optical power, and high p-n junction resistance [10]. To enhance capacitance ratio it is necessary to increase illuminated power density and decrease dark p-n junction capacitance. For maintaining of p-n junction resistance at sufficient level it is necessary to decrease p-n junction area and use low optical powers for control. It is worth noting than photovaractor bandwidth is determined by capacitance-resistance time constant. Therefore, in comparing with high-speed p-i-n photodiodes limited additionally by transit time, the thickness of the photovaractor absorption layer can be made rather large even for the high frequencies operation.

Fig.6 shows simulated p-n junction capacitance and resistance in the frequency range 1÷60GHz under zero bias voltage and different illuminated powers for the 10μm-diameter photovaractor with structure mentioned above. It is seen that at the frequencies 10÷60 GHz and optical control powers up to 0.2mW the p-n junction capacitance is almost not depended on frequency, resistance is well above of 50 Ω, and the capacitance ratio is about 2.

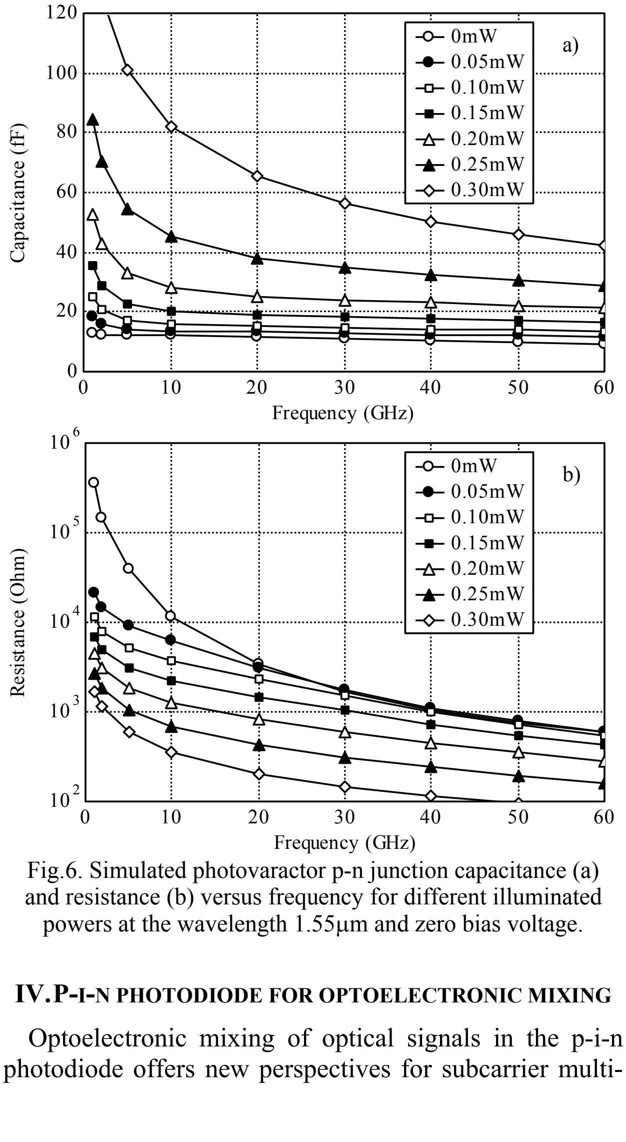

Fig.6. Simulated photovaractor p-n junction capacitance (a) and resistance (b) versus frequency for different illuminated powers at the wavelength 1.55μm and zero bias voltage.

IV. P-I-N PHOTODIODE FOR OPTOELECTRONIC MIXING

Optoelectronic mixing of optical signals in the p-i-n photodiode offers new perspectives for subcarrier multiplexed and radio-on-fiber systems. In this technique, the photodiode acts simultaneously as a optical detector and microwave mixer and there is no need to use a microwave local oscillator at the receiver part [1]. The most important parameter of the p-i-n photodiode in this case is the conversion efficiency, which is determined as the ratio of the microwave power measured at the converted frequency and the microwave power measured at the frequency related to the smallest optical signal in the linear mode of the same p-i-n photodiode.

Optoelectronic mixing of two intensity-modulated optical signals has been studied using three p-side illuminated p-i-n photodiodes placed in the pigtailed fiber optical module. Photodiodes had the same epitaxial structure, which consisted of 2μm-thick, $1.2\cdot10^{15}$cm^{-3} undoped n-$In_{0.9}Ga_{0.1}As_{0.23}P_{0.77}$ top layer, 3μm-thick, $1.2\cdot10^{15}$ cm^{-3} undoped n-$In_{0.53}Ga_{0.47}As$ absorption layer, 0.5μm-thick undoped n-InP buffer layer, and 400 μm-thick $3\cdot10^{18}$ cm^{-3} doped n$^+$-InP substrate. The p$^+$-region was formed by local diffusion of Zn into the wide bandgap n-InGaAsP top layer. The first p-i-n photodiode (PD1) had diameter 40 μm and p-n junction depth 2.2μm, the second (PD2) and the third photodiode (PD3) had diameter 30 μm and p-n junction depth 1.9μm and 1.8μm, respectively [11].

Fig.7 shows relative responsivity of the p-i-n photodiodes studied versus voltage for the frequency 0.2 GHz. It is seen that the photodiode response exhibits the highest nonlinearity near zero bias voltage. A decrease in the reverse bias voltage results in the decreasing of depletion region electric field, and part of the generated photocarriers recombine in the neutral region and do not contribute to the photocurrent. This results in the lowering of the photodiode response at the small bias voltages.

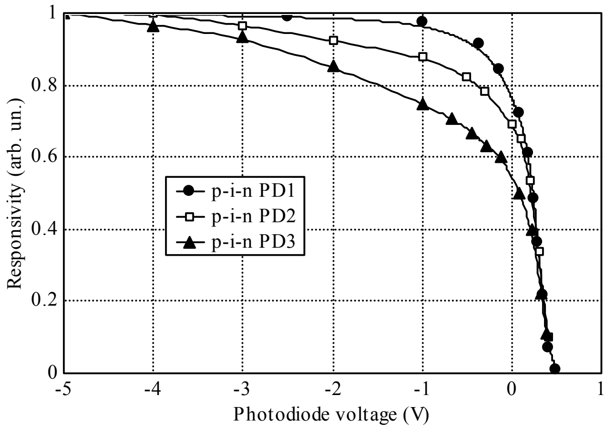

Fig.7. Relative responsivity of the p-i-n photodiodes versus voltage for the frequency 0.2 GHz.

The voltage dependence of the photodiode response is the dominant mechanism of the optoelectronic mixing in the p-i-n photodiode, which proceeds in the following way. The photodiode detects optical signal and generates a photocurrent. Due to the nonzero load resistance the detected signal produces oscillations of the voltage at the photodiode which result in oscillations of the photodiode responsivity. So the second optical signal is detected by the p-i-n photodiode with modulated responsivity, and, therefore, mixing products with sum and difference frequencies are generated.

Nonlinearity of the photodiode response is convenient to evaluate by the use of the nonlinearity parameter which is equal to the product of relative responsivity and its partial derivative with voltage. Fig.8 shows the nonlinearity parameter for studied p-i-n photodiodes. It is seen that the higher nonlinearity parameter is near zero bias voltages, the lower is this parameter in the region of the high reverse bias voltages.

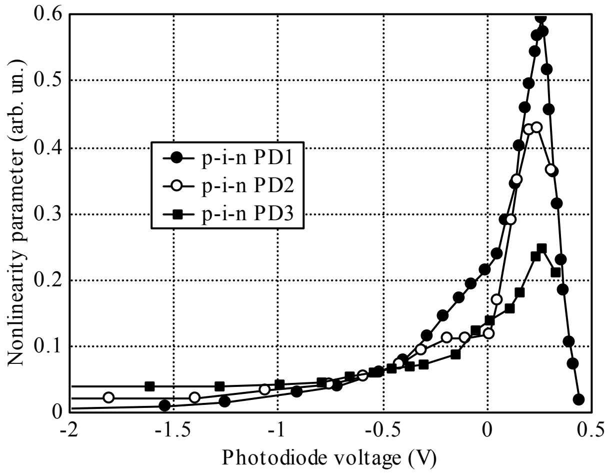

Fig.8. Nonlinearity parameter of the p-i-n photodiodes versus voltage for the frequency 0.2 GHz.

Fig.9 shows conversion efficiency for the p-i-n photodiodes investigated versus voltage in the case of the first optical signal at the wavelength 1.3 μm with modulation frequency 2.0GHz and the second one at the wavelength 1.51 μm and modulation frequency 0.2 GHz. It is seen that the higher conversion efficiency corresponds to the higher nonlinearity parameter of the p-i-n photodiode. Thus the nonlinearity parameter can be used as quality factor of the p-i-n photodiode when it is used as optoelectronic mixer.

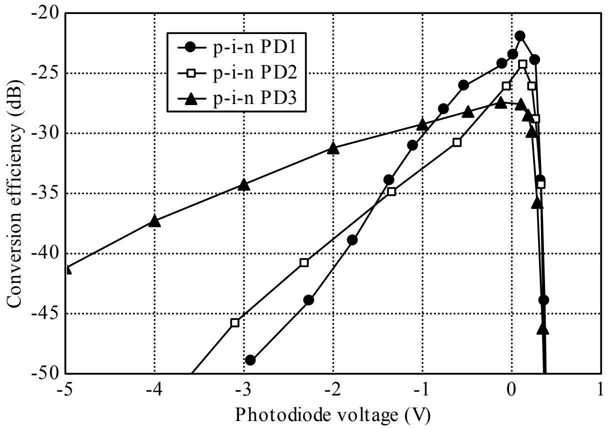

Fig.9. Conversion efficiency of the p-i-n photodiodes versus voltage in the case of the first optical signal at the wavelength 1.3 μm with modulation frequency 2.0GHz and the second one at the wavelength 1.51 μm and modulation frequency 0.2 GHz.

V. CONCLUSIONS

In this paper the design peculiarities of surface-illuminated InGaAs p-i-n photodiodes for different microwave applications have been considered. For photonic microwave generation application the main requirement to p-i-n photodiodes is the high saturation photocurrent. It is shown that the valance band discontinuity at the heterointerface p^+-InP/n-InGaAs strongly influences on this parameter. To overcome this problem the high p^+-region doping density, p^+-InGaAsP top layer with narrower bandgap than InP or thin graded bandgap n-InGaAsP layer between p-type top layer and absorption n-layer can be used. For optical control application the main requirements to p-i-n photodiodes are high capacitance ratio and low control optical power. It is shown that in the case of proper photovaractor design it is possible to obtain capacitance ratio more than 2 at the high frequencies 10÷60GHz under zero bias voltage and control optical powers lower than 1mW. For optoelectronic mixing application the most important parameter of the p-i-n photodiode is the conversion efficiency. It is shown that the photodiode nonlinearity parameter, which is equal to the product of relative responsivity and its partial derivative with voltage, determines the conversion efficiency and can be used as quality factor of the p-i-n photodiode, when it is used as optoelectronic mixer.

REFERENCES

[1] M. Tsuchiya and T. Hoshida, "Nonlinear photodetection scheme and its system applications to fiber-optic millimeter-wave wireless down-links", *IEEE Transactions on Microwave Theory and Techniques*, vol.47, no.7, pp.1342-1350, July 1999.

[2] K. Williams, M. Dennis, I. Duling, C. Villarruel, and R. Esman, "A simple high-speed high-output-voltage digital receiver", *IEEE Photonics Technology Letters*, vol.10, no.4, pp.588-590, April 1998.

[3] A. Hirata, M. Harada, and T. Nagatsuma, "120-GHz wireless link using photonic techniques for generation, modulation, and emission of millimeter-wave signals", *Journal of Lightwave Technology*, vol.21, no.10, pp.2145-2153, October 2003.

[4] T. Nagatsuma, "Photonic measurement technologies for high-speed electronics", *Measurement Science and Technology*, vol.13, pp.1655-1663, October 2002.

[5] Z. Szczepaniak, B. Galwas, and S. Malyshev, "Optically-switched microwave filter with the use of photovaractors in self bias mode", in *Proceedings of the 31th European Microwave Conference*, vol.1, London, UK, September 2001, pp.161-164.

[6] A. Chizh and S. Malyshev, "Modelling of the Photodiode in Various Microwave Applications", in *Proceedings of the 4rd International Conference on Advanced Semiconductor Devices And Microsystems*, Smolenice Castle, Slovakia, October 2002, pp.223-226.

[7] A. Chizh and S. Malyshev, "Modeling and characterization of microwave p-i-n photodiode", in *Proceedings of the 3rd International Conference on Advanced Semiconductor Devices And Microsystems*, Smolenice Castle, Slovakia, October 2000, pp. 239-242.

[8] K. Williams and R. Esman, "Design considerations for high-current photodetectors", *Journal of Lightwave Technology*, vol.17, no.8, pp.1443-1454, August 1999.

[9] S. Malyshev, B. Galwas, J. Piotrowski, A. Chizh, and Z. Szczepaniak, "Photovaractor for remote optical control of microwave circuits", *IEEE Microwave and Wireless Components Letters*, vol.12, no.6, pp.201-203, June 2002.

[10] S. Malyshev, and A. Chizh "P-i-n photodiodes for optical control of microwave circuit", *IEEE Journal of Selected Topics in Quantum Electronics*, vol.10, no.4, July 2004.

[11] S. Malyshev, B. Galwas, A. Chizh, J. Dawidczyk, and V. Andrievski, "Study of frequency conversion process of two optically transmitted signals to p-i-n photodiodes", in *Proceedings of the 15th International Conference on Microwaves, Radar and Wireless Communications*, vol.3, Warsaw, Poland, May 2004, pp.878-881.