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Modeling of Nonlinear Effects in Waveguide Silicon on Simox in Optimum conditions according to the Experiment

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ABSTRACT

This study concerns the modeling of non-linear operation of a silicon waveguide on an insulator of simox type with grating coupler in a dynamic regime, the simulation parameters are determined in accordance with the experiment, with the aim of achieving fast threshold optoelectronic switches. The optical non-linearities in the silicon are related to the change of the refractive index, and are used to obtain fast switching on the transmitted beam due to the propagation of the fundamental mode in the guide. The performances of these components are highly dependent of its rising time and its sensitivity. We will maximize the latter two. The model of non-linear operation of fast threshold optoelectronic switches are made in the dynamic regime based on the variations of the refractive index caused by both of the creation of free carriers and by the thermal effects due to the recombination of the carriers. This model allows, starting from the time variation of different diffracted intensities, to determine the operating range of the waveguide by adjusting key parameters such as: incident power density, the angular offset relative to the resonance.

Key words: Optical non-linearities, Simox, Switch, Waveguide.

1.INTRODUCTION

Control of electrical appliances by triggering a light pulse technique became more common as the use of pulsed lasers is widespread in many domains of physics. Even if this technique has made a huge improvement on the uncertainty of the time of onset of appliances constituting of laser chain, it is still inconvenient in many applications. The search for better accuracy on this point has led us to study and make an optoelectronic switch which the proper operation reduces this uncertainty, without having to add an additional element that is optical or electronic. This optoelectronic switch as a basic component admits one optical waveguide operating in the nonlinear mode. On both sides of this guide were implanted doped regions, forming a photoconductor [1,2] or a photodiode as in the case of our study. The resulting component generates, as soon as it receives a sufficient light power density, an electrical signal (photocurrent) faster than the incident light pulse which the intensity rises sharply from a low state to a high state causing a switching.

For application to Nd-Yag laser with the wavelength $\lambda = 1,06\mu m$ silicon on insulator has been used for long time to perform nonlinear waveguides [3]. Early studies were conducted on optoelectronic switches threshold with waveguide silicon on sapphire [4-6]. Nonlinear effects were observed on these waveguides, but the photocreated carriers' recombination of a lifetime less than a nanosecond, leads to a rapid development of thermal effects that alter the qualities of the switch within the domain of a few nanoseconds pulses [7]. Thus the SOI substrata of SIMOX type (**S**eparation by **Im**plantation of **OX**ygen) of the best crystallographic quality are increasingly used. Various studies have been conducted on SIMOX waveguides for diverse applications such as making spatial light modulators [8], optical switches [9,10], and photodetectors of photoconductive threshold power [1] [2]. The photoconductive were studied first have the disadvantage of high obscurity current and a relatively slow response time that depends on the lifetime of carriers (1µs) [1]. The material SIMOX is useful for integrated optics since the refractive index of the silica layer buried, much lower than that of silicon, provides an excellent containment of light in the surface layer. From silicon used as waveguide, more improvement of the quality of the interface silicon / buried sio$_2$ increases the lifetime of the carriers and reduces optical losses. The coupling of light in the waveguide is effected by means of a diffraction grating. A simulation taken in the linear regime allows to optimize the coupling in order to obtain the sharp resonances on the absorbed and transmitted intensities [11].

The objective of this simulation is to study the temporal evolution of intensities reflected, absorbed and transmitted, the simulation parameters are fixed according to the experiment. This optimizes the parameters of the waveguide, for fast switchings and contrasted using the nonlinear optical properties of silicon. These are related to the variation of the refractive index of the guide, depending on the number of photocreated carriers (electronic effects) and the variation of temperature and Joule effect (thermal effects).

2. PRESENTATION OF THE DEVICE

Figure 1 shows the basic structure of the optical waveguide devices on SIMOX with different light beams: The incident beam Ii forming an angle θ_i with the normal to the guide, and the transmitted beam It. The base component is a waveguide

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on SIMOX, formed by a stack of dielectric layers (Figure. 1), a thin silicon layer is forming the film guiding of *0,1µm* and a buried layer of SiO_2 of 0,45m of thickness. This latter has a refractive index significantly lower than that of silicon, resulting in an excellent containment of light in the silicon film used as a single-mode waveguide.

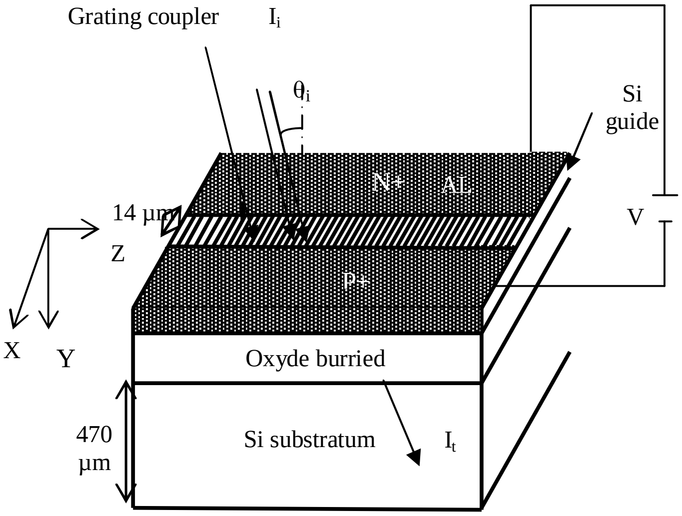

Figure 1 : Modelized structure

The light is coupled in the guide by a diffraction grating, and for a given angle θ_r we can excite the quide mode resonantly. A wavelength $\lambda = 1{,}06\mu m$ the silicon is slightly absorptive; the electron-hole pairs are generated in the structure. The distances between the doped areas and between the electrodes are respectively 14 and 24µm. The creation of carriers in silicon induces electronic effects which contribute to reduce the refractive index, in contrast to the evolution of thermal effects which act antagonistically. Nonlinear effects in silicon induce a variation of the refractive index and change the propagation constant of the guided mode. If θ_r is the resonance angle in the linear mode (negligible variation index) at time t = 0 we moves off resonance opting for an angle of incidence as $\theta_i = \theta_r + \delta\theta_0$, so that: $\delta\theta_0 \langle 0$. And progressively as the non-linear effects are formed and the refractive index decreases, the guide retunes producing a switching that results in a sudden variation of the transmitted beam. In this model the waveguide is assumed to be infinite and uniform illumination in the interelectrode space, We study the nonlinear phenomena in the perpendicular plan to the direction of propagation in the guide (plan xoy on Figure 1). This model is developed in two-dimensional geometry in order to calculate the temporal variations of the refractive index in the guiding film and their influence on the resonant mode.

3. MODELING OF NON-LINEAR REGIME

The optical nonlinearities of electronic origin result of the photocreation of a plasma of electron-hole pairs of density $\delta N(t)$. This is explained by a variation of an index of electronic origin [2] :

$$\delta n_e = K_e.\delta N(t) \tag{1}$$

The nonlinearities thermally induced in the photodiode resulting from the contribution of three phenomena: Auger recombination of photocreated carriers, thermalization of free carriers.

$$\delta n_{th}=K_{th}.\ \delta T(t) \tag{2}$$

K_e and K_{th} are constants of electronic and thermal nonlinearities, they are of opposite sign, these values are adjusted according to the experiment with the wavelength $\lambda = 1{,}064\mu m$ [2] : $K_e = +5.2*10^{+21}cm^{+1}/$, $K_{th}=5.8*10^{+4}K^{+1}$. The combined effect of the two index variations of electronic and thermal origin induces total variation index equal to:

$$\delta n_t=\delta n_e+\delta n_{th} \tag{3}$$

The latter causes a variation of the effective index of the guided mode and therefore a gap of $\delta\theta$ of resonance angle θ_r, corresponding to the resonant excitation of the fundamental mode TE_0. This shift is proportional to the variation of the index $\delta\theta=K\delta n_t$ where K is a proportionality constant which is equal to 60 [11]. The evolution of the temperature variation $\delta T(t)$ derived from the resolution of the classical equation of heat diffusion:

$$\frac{\partial \delta T(\vec{r},t)}{\partial t} - \Delta\delta T(\vec{r},t) = \frac{S(\vec{r},t)}{C} \tag{4}$$

Where $\vec{r}$: is the position vector, C : the heat capacity, and S is the heat source dissipated in the volume position $\vec{r}$. In our case, both linear steady and dynamical regimes that the resolution method best suited to multilayer systems is that of finite differences. In fact, the heat equation and the conditions at the various interfaces lead to a rather complex system of equations. Remember also that the substratum is at ambient thermostat for heat removal, according to the experiment. The mechanism of heat generation results from the contribution of various processes, which are:

Photocreated carriers recombination by Auger effect. The heat source that results is [1,2]:

$$S_r= [\ \gamma\ (\delta N)^3]Eg \tag{5}$$

γ represents the coefficient of recombination auger and E_g is the width of the forbidden band. The thermalization of heated free carriers by photon absorption, which implies a heating source given by [1,2]:

$$S_{apl} = [1-\eta(t)]\frac{A}{e_{si}} I_i(t)\cos\theta_i\ (\theta_i) \tag{6}$$

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η(t) is the time-dependent quantum yield, through a variation in the number of carriers and that of the temperature [1,2].

$I_i(t)$ is the incident light intensity. Since the heat sources are time-dependent, the variation of the number of carriers is determined for each given time t by solving the continuity equation:

$$\frac{d\delta N(t)}{dt} = G - R \qquad (7)$$

(We neglect the electric field and the carriers diffusion). G is the generation speed of the carriers; it is given by the following equation [2]:

$$G(t) = \frac{\eta(t)}{\hbar\omega e_{si}} A_{si} I_i(t) \cos\theta_i \qquad (8)$$

Here η(t) is the quantum yield of carrier pairs photocreation , $\hbar\omega$ represents the energy of the incident photons.

When we send an incident beam of intensity Ii on the structure, it results a fraction absorbed AI_i, a fraction reflected $R.I_i$ and another transmitted.TI_i. The relation of the uniqueness is checked (A + R + T = 1). A represents the absorptance, it is approximated by a Lorentzian function [2] :

$$A(\theta_i) = \frac{A_{Max}}{1 + \left(2\left(\theta_i - \theta_r\right)/\Delta\theta\right)^2} \qquad (9)$$

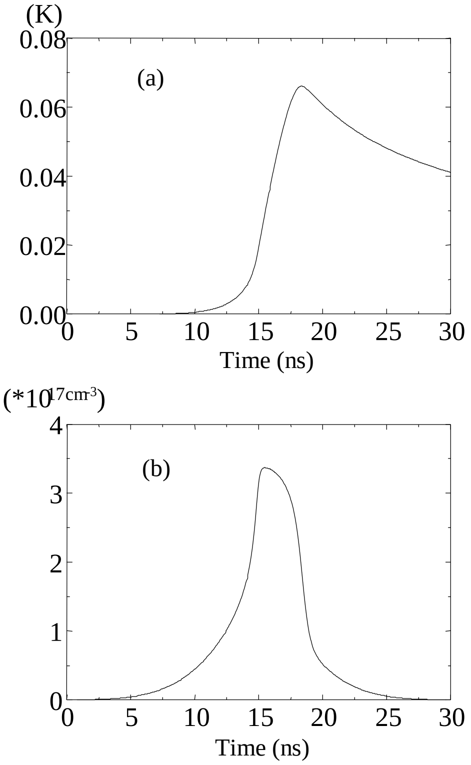
Where A_{max} = 0.17 is the maximum absorptance, θ_i, θ_r represent respectively the angle of incidence and the angle of resonance, and $\Delta\theta$ is the angular width at half maximum of the resonance associated with the excitation of the fundamental mode $\Delta\theta = 0{,}1°$ [1,2].

4. RESULTS OF THE SIMULATIONS AND DISCUSSION

The simulation parameters are set according to the experiment [2]. In these optimal conditions, two parameters are crucial for the performance optimization of the components; that is to say that response speed, the good switching contrast and high sensitivity, these are the incident power density and the angular offset relative to the resonance. To encourage non-linear effects of electronic origin which allow fast switching, throughout our study we don’t make resonance at t=0. We chose an angle of incidence $\theta_i = \theta_r + \delta\theta_0$, as que $\delta\theta_0<0$. And progressively as the non-linear effects that are formed and the refractive index decreases, the guide retunes producing a switching that results in a sudden variation of the intensity absorbed.

The waveguide device is illuminated with light pulses of 10ns (full width at half height of the static resonance) because transit time is very low. Considering an angular offset negative (initial disagreement), we calculated the evolution of all temporal quantities such as temperature variation δT, the number of photocreated carriers δN, the global variation in the refractive index δn_t that results from it, the resulting angular offset δθ and finally the evolution of diffracted intensities.

For an incident power density as : I_c = 50KW/cm^2, it is the threshold power [12] and for the angular offset $\delta\theta_0$=-0,1°, we calculate the evolution of different sizes (Figure 2).



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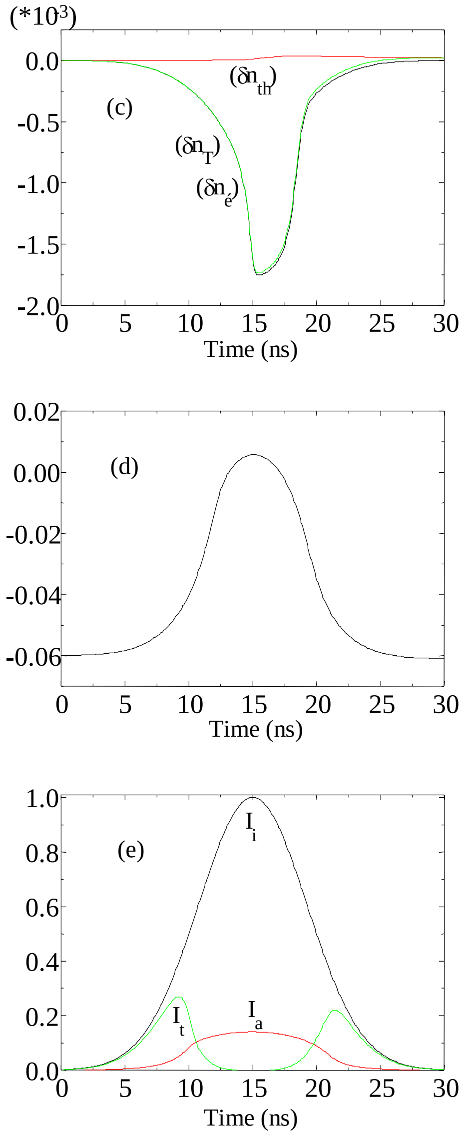
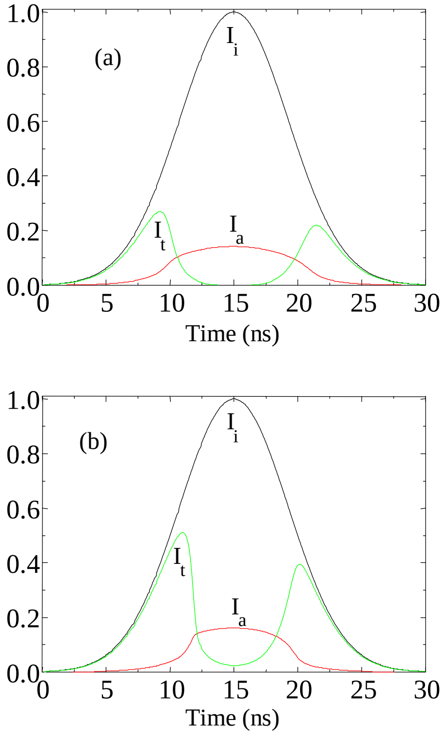


Figure 2: Temporal Evolution of Different Sizes for $\delta\theta_0$=-0,1° and for Power Density I_c=50KW/cm^2:
(a) : Temperature rise evolution, **(b) :** Number of carriers evolution, **(c) :** Contributions to the variation of the index, **(d) :** Resulting angular offset,
(e) : Absorbed and transmitted intensities evolution

There is a sudden change in the number of photocreated carriers (Figure 2-b), which results a negative change in the index of electronic origin δne, and a significant decrease in the value of the refractive index of silicon (Figure 2-c). Then follows a change in the resonance angle in relation to the initial disagreement $\delta\theta_0$, the value of which is proportional to the global variation in the index, such as : $\delta\theta_r = B\delta n_t$, with (B=60) [7], the resulting variation of the angular offset (Figure 2-d) is remarked $\delta\theta = \delta\theta_0 - \delta\theta_r$. A highly nonlinear behavior is highlighted on the transmitted intensity (Figure 2-e). In fact, the increase in absorptance resulting from angular retuning causes change of the power density absorbed during the growth phase of the light pulse. This accelerates the increase in the number of free carriers causing a runaway mechanism and leading to a contrast switching of electronic origin. It occurs to an index variation corresponding to the retuning of the system, that is to say to the passage through resonance when $\delta\theta = \delta\theta_0 - \delta\theta_r = 0$ (Figure.2-d). This relatively fast switching occurs for a value $\delta N \approx 3{,}24.10^{17} cm^{-3}$ of the concentration of electron-hole pairs at time t=15.08 ns.

In our study, the transit time is very low, so we need a high incident power density for the first switching of electronic origin, when the temperature increases; we notice that there is a second switch of thermal origin. This second switch is not very pronounced and not influent on the functioning of the photodiodes device as a fast switch threshold power. After having demonstrated the existence of nonlinear effects in the structure, we will study the evolution of these depending on the incident power density and angular offset. By determining the power density incident by *I_c=50KW/cm^2* (value causing the switching for angular offsets (*$\delta\theta_0$=-0,06°, -0,08°, -0,1°,-0,2°*), we study the evolution of the diffracted intensities depending on angular offsets mentioned above (Figure 3).



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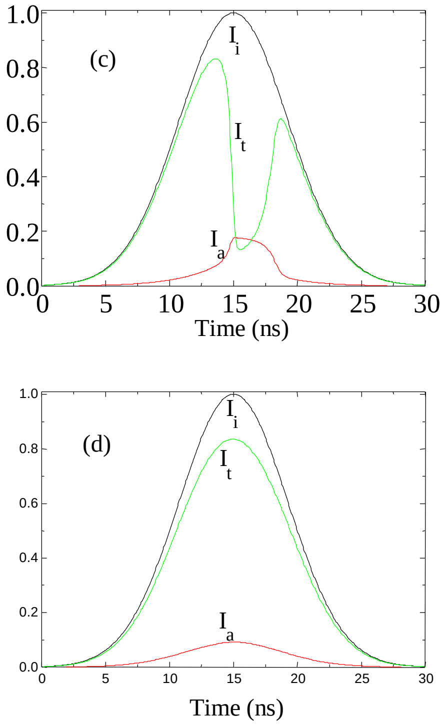


Figure 3 : Variation of Different Diffracted Intensities Depending on the Initial Angular Offset for I_c=50KW/cm^2: **(a) :** δθ0=-0,06°, **(b) :** $\delta\theta_0$=-0,08°, **(c) :** $\delta\theta_0$=-0,1°, **(d) :** $\delta\theta_0$=-0,2°

We notice in these different figures that for the values of the initial angular offset increasingly large, the switching time of the transmitted intensity reaches more lately, but switching becomes faster. We see that for $\delta\theta_0$= -0,2°, the switching did not occur.

For this, we consider the shift of -0.2° according to the experiment [2]. We search the optimal power, we find that for I_c=400KW/cm^2, taking angular offsets increasingly large ($\delta\theta_0$=-0,15°, -0,18°, -0,2°, -0.22°) (Figure 4), there is a significant improvement in speed. The contrast defined as the ratio between the maximum value of the power transmitted off-resonance value and the value of the power transmitted with resonance also increases. The maximum value of the intensity absorbed increases depending on the angular offset, the sensitivity is better.

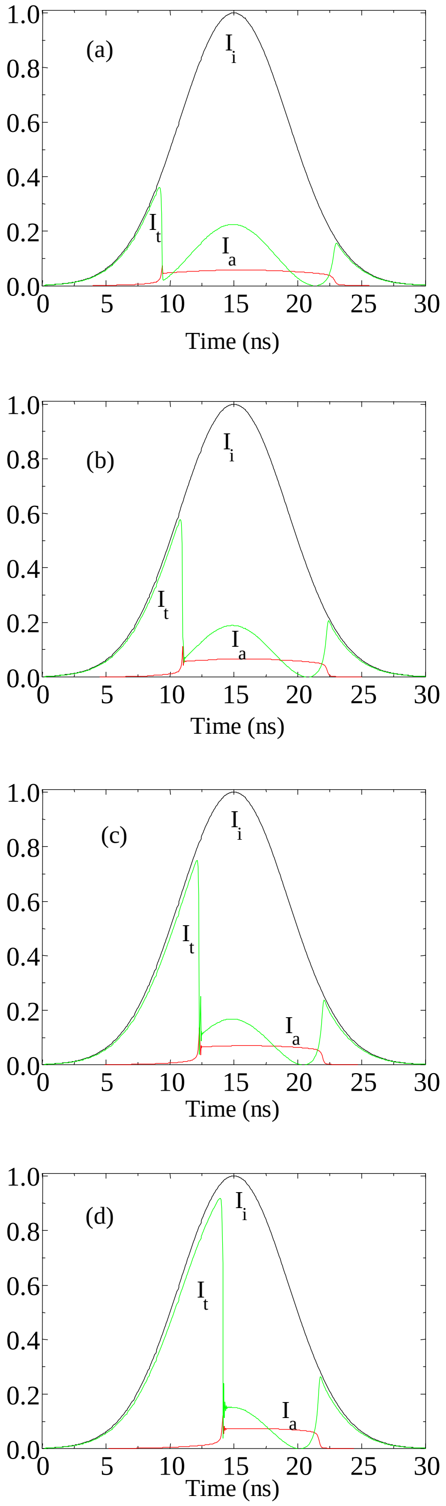
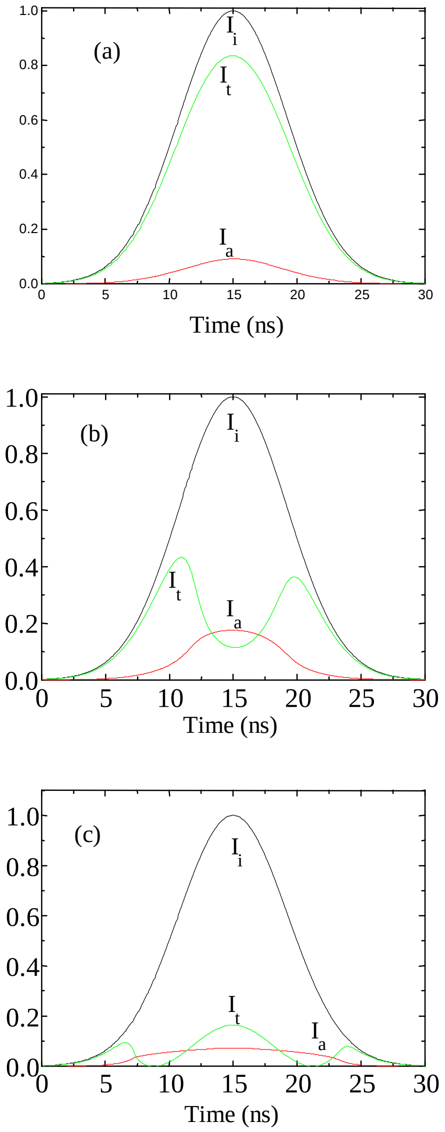


Figure 4 : Variation of Different Diffracted Intensities Depending on the Initial Angular Offset for I_c=400KW/cm^2: **(a) :** δθ0=-0,15°, **(b) :** $\delta\theta_0$=-0,18°, **(c) :** $\delta\theta_0$=-0,2°, **(d) :** $\delta\theta_0$=-0,22°

By determining the angular offset by $\delta\theta_0$=-0,06°, we study the evolution of nonlinearities effects depending on power density incident (Figure 5).

In this case the switching happens earlier in time, when the incident power density increases, it becomes less rapid. For fairly high incident intensities (Ic ≥ 300KW/cm^2), we observe a very low pronounced switching, which tends to disappear for higher intensities.



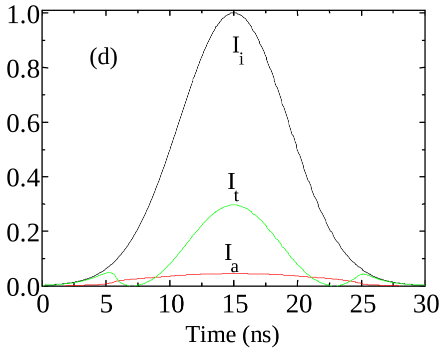
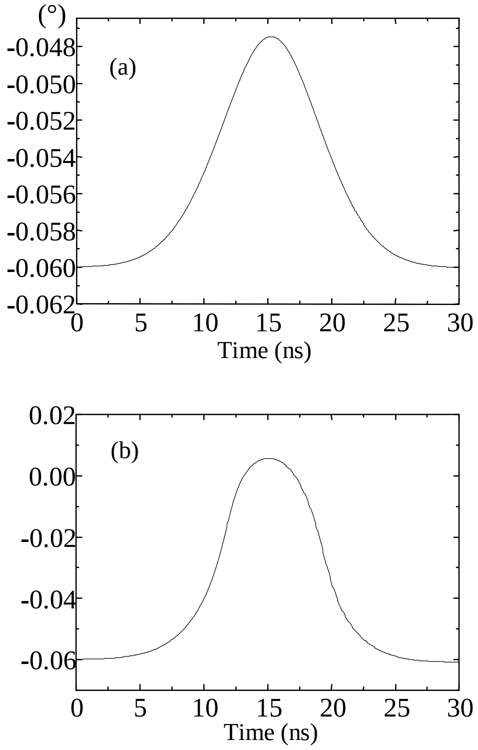


Figure 5: Simulation of the Dynamic Operation of the Device at Any Optical for $\delta\theta_0$=-0,06° with Different Values of the Peak Intensity: **(a) :** I_c =10 KW/cm^2, **(b) :** I_c =30 KW/cm^2, **(c) :** I_c =150 KW/cm^2, **(d) :** I_c =300 KW/cm^2

The curves representing the temporal variation of the resulting angular offset (Figure 6) show that the power density I_c = 10KW/cm^2 induces a variation insufficient for switching, there is not compensation of the angular initial fixed and therefore not passing through resonance.



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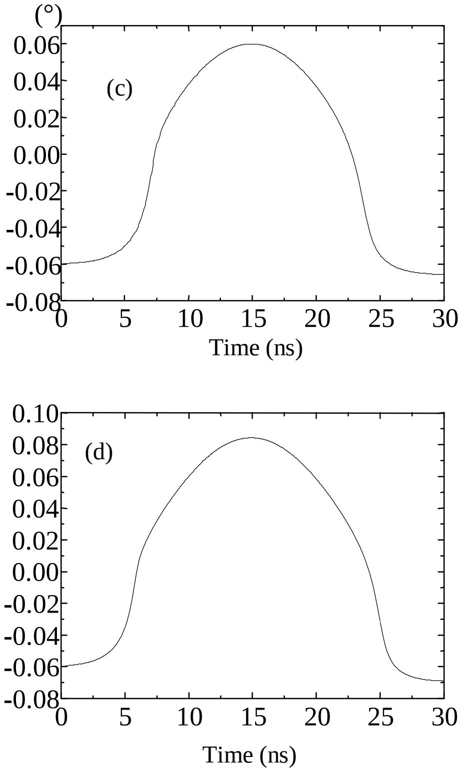

Figure 6: Temporal Evolution of the Angular Offset Resulting for $\delta\theta_0=-0,06°$ and for Various Values of the Incident Intensity: **(a) :** I_c =10 KW/cm^2, **(b) :** I_c =30 KW/cm^2, **(c) :** I_c =150 KW/cm^2, **(d) :** I_c =300 KW/cm^2

As soon as we increase the light intensity the equation $\delta\theta_0 = \delta\theta_r$ is verified and resonance passage becomes possible. This study has highlighted the existence of a fast switching of electronic origin on the transmitted beam. There is also a second thermally induced switching which is not very pronounced and not influent on the functioning of the device (photodiode) as fast switch threshold power. We determined the area of operation of the switch regarding to the incident intensities as well as the initial angular offsets depending to the resonance.

5. CONCLUSION

The purpose of our work was to study the nonlinear effects in a silicon waveguide structure on insulator of SIMOX type with grating coupler in optimum conditions according to the experiment, the goal being to model photodiodes of fast threshold. We have developed a simulation model which takes into account both the number of excess carriers in the structure and local variations in temperature. The simulation results in pulsed regime highlight the existence of two switches on the transmitted beam ; one of electronic origin and another of thermal origin, the second switch is not very pronounced and not influent on the functioning of the device as a fast switch. The parameters governing the operation of the waveguide Si on SIMOX are: the angular offset relative to the resonance and the incident power density. We therefore, determined the operating range of this fast switch, as regards the power densities and the angular offset relative to the resonance, to obtain the fastest and most contrasting switching on the transmitted beam. We can conclude that these components can be under certain operating conditions that may interest the applications using laser powers.

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