Electromagnetic modeling and characterization of an optically-controlled microwave phase shifter in GaAs integrated technology

C. Tripon-Canseliet[1], S. Faci[1], F. Deshours[1], C. Algani[1], G. Alquié[1], S. Formont[2], J. Chazelas[2]

[1]LISIF-UPMC, MIME Group, 3 rue Galilée, 94200 Ivry sur Seine, France
[2] THALES Airborne Systems, 2 av Gay Lussac, 78 852 Elancourt , France

Abstract — **A state of the art of the modeling of microwave photoswitching devices is exposed. A new 3 D electromagnetic modeling allows the design of an optically-controlled microwave phase shifter microwave starting from the traditional circuit of a microwave photoswitch. Measurements of the parameters S of this optically-controlled microwave phase shifter attests the function of this circuit by optical way and highlights the interest of the integration of this new type of microwave phase shifters in systems of antennas arrays. A new optically-controlled microwave phase shifter with a patented structure is under development.**

I. Optically-Controlled Microwave Switching Principle

The optical control of microwave signals makes possible the design of new ultra high frequencies systems with a large bandwidth. We thus propose here a new microwave phase shifter with an external optical command whose operation rests on the photoswitching of microwave signals by photoconductive effect.

The photoconductive effect intervenes in a semiconductor material submitted to an optical excitation at an optical wavelength included in its spectral band of absorption. During the illumination, a plasma layer of electron/hole pairs, characterized by a photoconductance Gg equivalent to a photoresistance R_g, is generated on the level of the illuminated area, modifying locally the conductivity of the semiconductor material.

The insertion of this effect in a device in integrated technology (Fig. 1) can be carried out by a simple circuit consisting of a transmission line discontinuity on a semiconductor substrate. The resulting optically-controlled microwave photoswitch leads to the optical control of the propagation of a microwave signal crossing the interruption of line, in amplitude and in phase. The microwave photoswitching device is then characterized by a complex quantity called ON/OFF ratio (1).

II. Electrical and 2.5 D Electromagnetic Simulations of a Microwave Photoswitching Device

A. Classical Electrical Modeling

In the darkness (OFF state), the equivalent electrical model of an optically-controlled microwave photoswitch comprises a series capacitance Cg and two shunt capacitances C_P, according to the model of Gupta [1]. At ON state, illumination is synthesized by a conductive layer with a thickness d_e (3) and a conductivity $\Delta\sigma_m$ corresponding to the conductivity growth in the illuminated substrate area induced by light. This plasma layer is equivalent to a Rg photoresistance (2), in parallel on the Cg capacitance. The expression of Rg depends on the physical parameters of the optical beam and the semiconductor material, according to a model developed by W Platte and B Sauer [2]. This model is only valid for a constant illumination. However it does not take into account the local variation of the permittivity of the semiconductor substrate due to illumination. For an optical excitation modulated in magnitude, it is necessary to use a nonlinear electric modeling of the photoconductive effect depending on time, parameters of the semiconductor substrate and dynamics of the carriers in this substrate [3].

B. Classical 2.5 D Electromagnetic Modeling

The laser illumination of the substrate at continuous optical power can be modeled artificially by a finite conductive layer defined like a metalized hole with a thickness d_e. A planar mesh of the traditional photoswitching circuit with rectangular electrodes leads to simulations results by the method of the moments, close to measurements, in the case of a constant illumination [4].

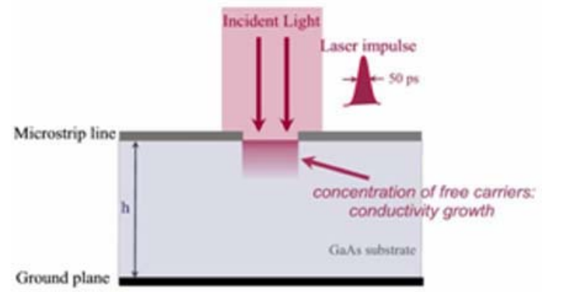
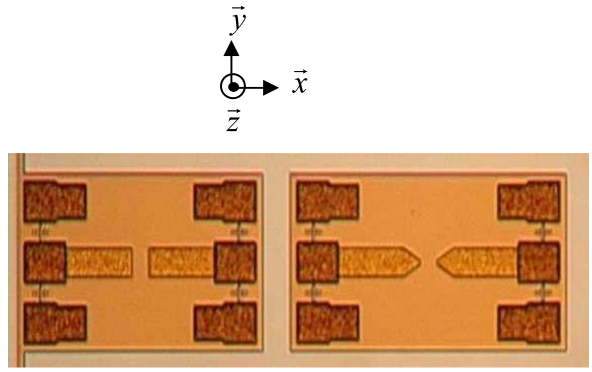


Fig. 1: Photoconductive microwave switch description in microstrip technology.



(a) (b)

Fig. 2. Photographs (Top views) of optically-controlled microwave photoswitching devices on GaAs substrate with a (a) rectangular and (b) tapered electrodes geometry

$$\Re_{ON/OFF} = \frac{S_{21}(ON)}{S_{21}(OFF)} = R_{ON/OFF} e^{i\Delta\varphi_{ON/OFF}} \quad (1)$$

$$R_g = \frac{1}{G_g} = \frac{L_g\left(1-\alpha^2L^2\right)}{w_{eff}\Delta\sigma_{ph}\left(\frac{1}{\alpha} - L\frac{\alpha L^2 + v_s\tau}{L + v_s\tau}\right)} \quad (2)$$

$$d_e = \frac{1}{\alpha}\left[\frac{L(1+\alpha L)}{L + v_s\tau}\right]\left[\frac{1}{\alpha L}\left(\frac{\alpha L^2 + v_s\tau}{L + v_s\tau}\right)\right]^{\frac{\alpha L}{1-\alpha L}} \quad (3)$$

Electrodes Geometry	Magnitude (dB)		Phase (°)	
	10 GHz	20 GHz	10 GHz	20 GHz
Rectangular (classique)	2.79	1.92	14.0	10.2
Tapered (optimized)	0.90	0.59	24.2	12.1

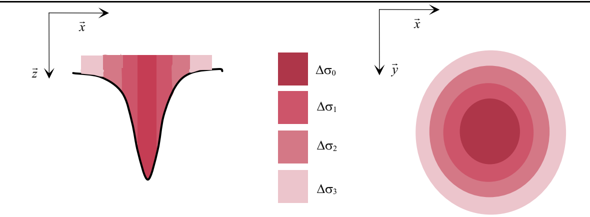
TABLE I: Measured ON/OFF Ratio of an optically-controlled microwave phase shifter (tapered electrodes) compared to results from a classical microwave photoswitch (rectangular electrodes).

III. Optically-controled Microwave phase Shifter Design from 3D Electromagnetic Simulations

To carry out an optically-controlled microwave phase shifter starting from the classical structure of a photoswitching device (fig. 2a), the geometry of the planar microwave circuit was optimized in order to perform only a phase shift of the microwave signal feeding the system by optics. A tapered discontinuity geometry is selected (Fig. 2b). In this configuration, illumination takes place only on the edge of one of the electrodes forming the discontinuity in order to locally modify its impedance. Thus an improvement of the microwave magnitude is prevented since the position of the optical beam at ON state does not affect the existing coupling between the two tapered electrodes at OFF state.

A new 3D electromagnetic modeling of illumination, by extension of the previous 2.5 D modeling, allows microwave behavior prediction in frequency domain of the optically-controlled microwave phase shifter according to the position of the optical beam, its diameter and incident power P_{opt}. The absorption of the laser optical beam is represented by a plasma layer with the same permittivity as the semiconductor substrate, a thickness d_e and a conductivity corresponding to the conductivity growth $\Delta\sigma_m$. This conductivity can be also to be variable in magnitude, in the plane of the microwave circuit, in accordance with the Gaussian profile of the power of the applied optical signal. Compared with the preceding one, this modeling, based on the finite element method, brings flexibility in use as well as possibility of simultaneous parametric simulations.

One of the advantages of this new method of simulation adapted to optically-controlled microwave devices, is to be able to predict the behaviour of these circuits for an illumination with a tuneable space position. Electromagnetic simulations become a necessary tool to study the influence of an illumination allowing the establishment of the photoconductive effect, which could be not centered at the middle of the microwave transmission line discontinuity. These simulations also show the interest of the development of a microwave photoswitching device with tapered electrodes under an illumination with a spatial offset from the center of the device top face, in order to design of a photo phase shifter working by photoconductivity. Indeed, by considering a Cartesian coordinates system (x, y, z) as indicated on figure 2, a displacement of illumination along $\vec{x}$ and/or $\vec{y}$ allow a control and a reduction of the microwave coupling between the two electrodes constituting the discontinuity. In this case, a tapered geometry of electrodes leads to the single benefit on a microwave phase shift, by comparison with a traditional electrode geometry which induces a more significant reflection of the optical signal by the metal rectangular electrode around discontinuity.



$$I\left(x,y,z'_{Air/SC}\right)=\frac{2P_{opt}}{\pi W\left(z_{Air/SC}\right)}\exp\left[-\frac{2\left(x^2+y^2\right)}{W^2\left(z'_{Air/SC}\right)}\right] \quad (4)$$

$$\Delta\sigma\left(x,y,z\right)=H\left(z\right).F\left[I\left(x,y,z'_{Air/SC}\right)\right] \quad (5)$$

Fig. 3 : Spatial profile of optically-induced substrate conductivity related to a Gaussian optical beam (single mode case)

Δy \ Δx	0 um	10 um	20 um	30 um
0 um	1.23 / 42.1	1.90 / 47.0	1.25 / 40.3	0.7 / 11.9
10 um	1.82 / 36.8	2.02 / 32.0	1.78 / 26.3	0.88 / 20.4
20 um	2.26 / 27.1	2.54 / 26.5	1.84 / 23.4	1.39 / 19.2
30 um	2.42 / 22.7	2.28 / 21.5	1.88 / 19.4	1.24 / 16.4

TABLE II: Magnitude (dB)/Phase (°) of simulated ON/OFF ratios at a microwave frequency of 20 GHz for various positions of the optical beam compared to its central position (middle of the microstrip discontinuity) - Optical power of 140 mW - Diameter of beam of 70 um

Table II gathers in a matrix representation, simulated ON/OFF ratios in magnitude and phase obtained at a microwave frequency of 20 GHz, for several spatial offsets of illumination in the xOy plane, by steps of 10 µm. It highlights the importance of the position of the optical excitation to privilege a single phase shift of the microwave signal by optics, in particular by the illumination of only one electrode. For example, an illumination intervening at a distance of 30 µm and 10 µm along $\vec{x}$ and $\vec{y}$ axis respectively from the center of the discontinuity introduces a phase shift of 20° of the microwave signal with a very low change of magnitude of 0.88 dB. The particular spatial offset of illumination along $\vec{x}$ axis from the center of the discontinuity induces a decrease of the isolation between the two working ON and OFF states in amplitude with a considerable phase shift of the radiofrequency wave.

In simulation, the optical command modeled by a plasma layer is adapted in terms of diameter of cross section, conductivity and thickness whose values are extracted by identification with microwave measurements results carried out on existing samples with a traditional discontinuity and which are used as a reference. This stage of calibration in the modeling procedure then helps for the evaluation of the focus state of the incidental optical beam at the air/substrate interface, and also for the study of the effect of the optical beam cross section dimension on the microwave ON/OFF ratio value of the device.

Finally, laser illumination can be detailed spatially by various concentric layers defined by variable conductivity and identical thickness values, according to a Gaussian profile in the plane of the microwave circuit (Fig. 3). For example, intensity of a single mode optical beam is expressed as in equ. (4) in Cartesian coordinates system where $z'_{Air/SC}$ defines a fixed z-position of the optical fiber end from the top of the optically-controlled MMIC. Substrate conductivity change is then calculated from (4) at a spatial point (x,y,z).

IV. Microwave Measurements of an Optically-Controled Microwave Phase Shifter

S-parameters measurements of the optically-controlled microwave phase shifter realized on GaAs substrate with UMS technology process have been executed under microwave probes in a 0.05-40 GHz microwave frequency range. These experimental results reveal phase shifting associated to a quasi-constant magnitude of the microwave signal thanks to an optical signal at a wavelength of 671 nm and an incident optical power of 140 mW. Measured ON/OFF ratios of the optically-controlled microwave phase shifter and a traditional optically-controlled microwave photoswitch with the same technology are referred in Table I. The results from 3 D electromagnetic simulations of the optically-controlled microwave phase shifter are in conformity with measurements and enable the extraction of physical characteristics such as the position, the diameter and the power of the optical beam at the surface of the circuit.

For example, an increase in the microwave signal phase shift of 10° at a frequency of 10 GHz feeding the microwave photoswitching device with tapered electrodes is obtained thanks to optics, compared to a device with rectangular traditional electrodes. In terms of insertion losses, it becomes necessary to improve this new type of microwave optically-controlled phase shifter. Optimizations of this system have been studied in continuity with measurements obtained from a patented structure [5]. New samples are under process on GaAs substrate.

V. Optimizations of the Microwave Phase Shifting Device

In order to optimize the photoswitching device in terms of insertion losses and phase shifting, the planar microwave device topology must be refined. The first option uses design optimizations performed from a patented topology which has to be reconfigured with tapered electrodes [5].

The second choice could consist of reducing the line discontinuity length to maximize transmission coupling which does not affect the ON/OFF phase shifting.

The third possibility concerns the substrate material used. By adopting a low permittivity substrate with a local semiconductor patch suitable for photoswitching operation, insertion losses are minimized with a guaranteed ON/OFF ratio.

All these optimizations are in study.

VI. Conclusion

A state of the art of the modeling of photocommutateurs microwaves is exposed. A new 3D electromagnetic modeling allowed the design of a optically-controlled microwave phase shifter starting from the traditional circuit of photoswitching. The frequency domain S-parameters measurements of this optically-controlled microwave phase shifter attest the function of this circuit by an optical command and highlight the interest of the integration of this optically-controlled microwave phase shifter in systems of antennas arrays in integrated technology thanks to optics. A new optically-controlled microwave phase shifter with a patented structure is under development.

Acknowledgement

The authors wish to thank the UMS foundry for the samples process which led to significant measurements results.

References

[1] K.C. Gupta, R. Gar, I. Bahl, P.Bartia, « Microstrip lines and slotlines », Ed. Artech House, p.108, 1986.

[2] W. Platte and B. Sauerer, «Optically CW induced losses in semiconductor coplanar waveguides», IEEE MTT, Vol. 37, No. 1, pp 139-148, January 1989.

[3] C. Canseliet, C. Algani, F. Deshours, G. Alquié, S. Formont, J. Chazelas, «Optoelectronic modelling of high speed modulated optically-controlled Gallium Arsenide microwave switches»,, URSI, Maastricht, Netherlands, August 2002.

[4] C. Algani, F. Deshours, C. Canseliet, G. Alquié, S. Formont, J. Chazelas, «Influence de la puissance optique et de la fréquence microonde sur la réponse d'un photocommutateur GaAs », Optique Hertzienne et Diélectrique , Le Mans, France, September 2001.

[5] C. Canseliet, C. Algani, F. Deshours, G. Alquié, S. Formont, J. Chazelas, « A Novel Optically-Controlled Microwave Switch
On Semiconductor Substrates for an ON/OFF Ratio Enhancement », European Microwave Conference, Munich, Germany, October 2003.