Electromagnetic Analysis of Optoelectronic Devices Applied to the Study of a Sampler and an Autocorrelator

Lydie Armengaud, Michèle Lalande, Bernard Jecko, *Member, IEEE,*
Nicolas Breuil, Alain Barthelemy, and Marc Cuzin

Abstract—**In this paper, an optoelectronic sampler and an autocorrelator are described. The devices are made with microstrip propagation lines, and ultra-rapid photoconductive switches are integrated in the same substrate. These devices are studied along two interacting directions: sampler description and operation, and electromagnetic study. In particular, the electromagnetic study is discussed here. The purpose of the first is to understand the electromagnetic behavior of the optoelectronic sampler. The second study enables us to simulate the autocorrelator operation in order to characterize the ultra rapid photoconductive switch.**

I. Introduction

With the development of mode-locked lasers and new methods for preparing high speed materials, it has become possible to extend the response time of photoconductors into the picosecond range [1]. These photoconductors which can convert ultra fast optical pulses to ultra fast electrical pulses can be used as pulse generators or as sampling gates [2]–[4]. In order to sustain these advances, the development of optoelectronic devices must be up to the challenge.

For example, thanks to advances in these technologies, it is possible to characterize monolithic millimeter-wave integrated circuits [5]. Microwave measurements have long been dominated by frequency domain instrumentation but with high speed time domain techniques, results can be obtained over broad frequency ranges in a single experiment. Optoelectronic or electro-optic sampling techniques permits to obtain complex reflexion and transmission parameters [6]. Several properties of antennas can be determined also using photoconductive pulse generation and sampling (bandwith, radiation, and polarization patterns).

For fusion experiments, ultra-fast phenomena which are not easily repetitive must be observed and can not be studied with oscilloscopes. CEA/LETI (“Commissariat à l'Energie Atomique”) is developing an instrumentation system capable of analyzing an ultra fast pulse which is emitted once only [7]. The originality of this optoelectronic device is a single acquisition of all the sampled signal. An electromagnetic study permits to show the feasibility of this device. Thanks to the electromagnetic study, CEA/LETI is building a sampler which makes use of microelectronic technology.

The other optoelectronic device presented in this paper is an autocorrelator which is able to determine several points of a single pulse autocorrelation function (light, x-rays, ionizing pulses). The device requires two photoconductors, one of which is a pulse generator and the other a sampling gate. From the experimental autocorrelation function, it is difficult to deconvolve to deduce the photoconductor response. An electromagnetic study permits to determine the photoconductor switches response This study takes the capacitance coupling created by the photoconductor gap and the phenomena caused by the high frequencies signal (dispersion, radiation) into account. The method consists in modifying the response of the photoconductive switch until the autocorrelation function determined by simulation is similar to the one obtained by measurement.

So, we will describe two devices: an optoelectronic sampling device and an autocorrelator. Then, the electromagnetic method (finite-difference time-domain method (FDTD) method) used to analyze these devices is presented briefly. First developed by Yee [8], FDTD simulation has been applied by many investigations to a wide range of electromagnetic problems. This method is well adapted to propagation analysis in the microwave and millimeter range [9], and particularly adapted to study devices which propagate fast transient states such as these generated by a short laser pulse [10], [11]. On the one hand, the electromagnetic analysis of an optoelectronic sampler is described, and on the other hand, the autocorrelation function is determined by the simulation, in order to characterize the photoconductive switch.

II. Description and Operation of Two Devices

A. Sampler

The sampler is represented in Fig. 1. The device consists of one propagation line and N sampling cells.

Every cell consists of:

1) 1 photoconductor;
2) 1 sampling line;
3) 1 memory capacitor.

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L. Armengaud and M. Lalande are with the RIMOC (Research Institute on Microwave and Optical Communications), University of Limoges, 19100 Brive, France.

B. Jecko, N. Breuil, and A. Barthelemy are with RIMOC, 87060 Limoges Cedex, France.

M. Cuzin is with the LETI (CEA–Technologies Avancées), CENG, 38054 Grenoble Cedex 9, France.

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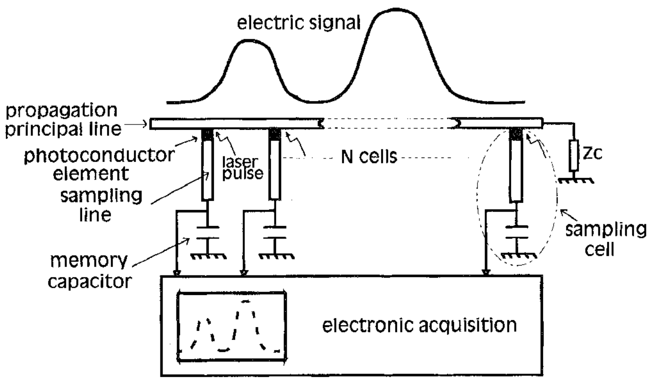

Fig. 1. Optoelectronic sampler.

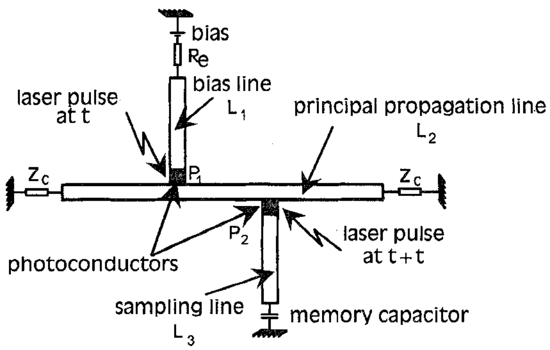

Fig. 2. Autocorrelator.

The lines are microstrip lines which have the same characteristics ($W = 120\,\mu$m and $H = 130\,\mu$m). All the microstrip lines have the same dielectric substrate (sapphire substrate $\varepsilon_r = 9.95$).

The optoelectronic sampler is a device capable of getting several points of a single pulse. Sampling consists in simultaneously switching off N photoconductor elements with a short laser pulse and reading the collected electric charges. The electric pulse to be sampled is transmitted on the propagation line with a matching end. When the signal has been entirely distributed along the line, a laser pulse illuminates all the photoconductor simultaneously. Then, every sampling line propagates a part of the signal which polarizes the photoconductor to the memory capacitor. The charge stored by the capacitors makes it possible to reconstitute the sampled signal. The closer the sampling lines, the better the reconstitution.

To suit the applications of the optoelectronic sampler, the propagation line must be able to transmit signals (200–300 ps) whose frequency bandwidth is up to 10 GHz, and the sampling lines must be able to transmit the charge of ultra fast pulses (8 ps). The sampling resolution must be equal to 18 ps. The frequency spanned by the electric pulses from the photoconductor, can be a few hundred gigahertz.

B. Autocorrelator

The device is represented in Fig. 2. It is made by CEA/LETI. The device is made up of metallic striplines combined with a photoconducting thin film. When interacting with a photoconductor element connected to the bias, an electric pulse dependent on the light pulse is created and propagates along the propagation line. The other photoconductor connected to the capacitor is illuminated after a delay time τ_i.

The collected charge is proportional to the $\int f(t) \times f(t+\tau_i)\,dt$ value for τ_i of the signal autocorrelation function [12].

For different values of τ_i, all the points of the autocorrelation function will be determined. For the sake of the experiment, the pulse is obtained from a mode-locked and frequency-doubled Nd : YAG laser. The wavelength of the pulse is 532 mm. The average power is about 150 nJ. The biasing potential of photoconductor P_1 is 150 V.

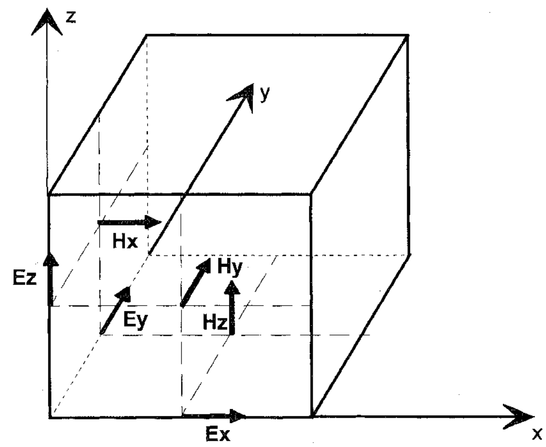

Fig. 3. Electromagnetic components in a cell.

III. Electromagnetic Analysis of the Behavior of the Two Devices

A. Adapting the Numerical Method for Electromagnetic Analysis

Results are obtained by using a finite difference time domain algorithm (FDTD) which gives direct solutions of Maxwell's time dependent curl equations. Maxwell equations are first differential equations that can be written thus

$$cur\,\vec{E} = -\,\mu\,\frac{\partial \vec{H}}{\partial t} \tag{1}$$

$$cur\,\vec{H} = -\,\varepsilon\,\frac{\partial \vec{E}}{\partial t} + \vec{j}. \tag{2}$$

The Maxwell equations are discretized in the space and time domains by using a Taylor development of the third order. Space discretization is made according to the scheme developed by Yee [8].

To analyze an open structure, the structure and the surrounding space must being divided into elementary parallelepipeds called cells. The six electromagnetic components are determined on each cell as shown in Fig. 3. Such a choice permits to center the space derivatives. The time domain derivatives are centered by calculating the electric and magnetic fields at different half time steps.

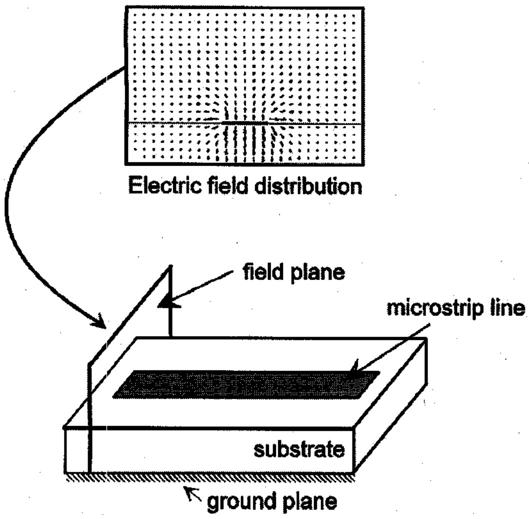

Fig. 4. Microstrip feed.

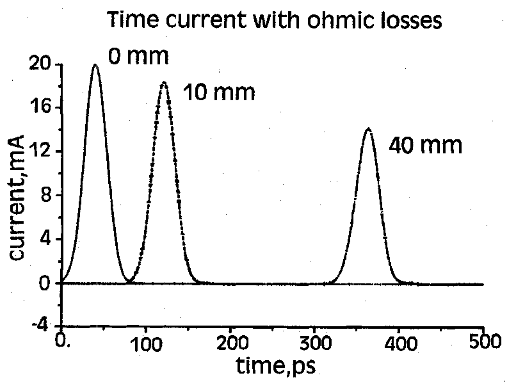

Fig. 5. Time current in various planes for a propagation line alone.

As it is impossible to cell infinite space numerically, open space simulation is achieved by adding absorbing media around the celling [13].

The use of parallelepiped cells makes it possible to accurately modelize volumes and surfaces. For example, the FDTD method has been applied to a microstrip bend characterization and a good similarity between theoretical and experimental results validates the theoretical method [9]. This method must be adapted to analyze the optoelectronic devices.

Up to now, the feed method for the line has consisted in simulating a conductor strip perpendicular to the line. At one end of the strip, vertical electric fields are applied on the whole width [9]. The discontinuity which is created by the feed, generates higher order modes or surface waves or free space waves in particular when the spectrum required for transmission covers a large bandwidth in the frequency domain. The optoelectronic devices propagate ultra fast pulses. So, a new method has been developed. The new line feed consists in obtaining the static map of the electric field, thanks to the resolution of Laplace's equation in a plane perpendicular to the propagation vector (Fig. 4). The field amplitude is modulated by any pulse form.

Another adaptation of the electromagnetic tool concerns the simulation of photoconductor operation. When the photoconductor is illuminated, it generates a pulse which depends on the characteristics of the laser pulse, the biasing voltage and the characteristics of the photoconducting material. Surface conductivity, which is a function of time, is applied to the photoconductor site to simulate the photoconductor response. The amplitude of the photogenerated current depends on the bias potential and the maximum amplitude of the conductivity. The simulation by the FDTD method permits us to allow for the capacitance coupling created by the gap.

Consequently, this method is used for the calculation concerning the optoelectronic sampler and an autocorrelator.

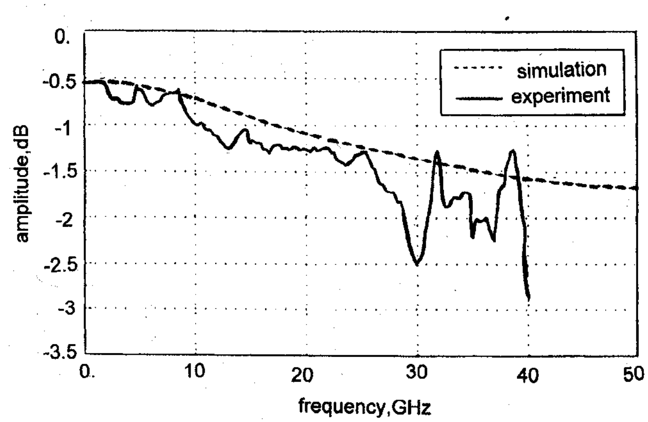

Fig. 6. Comparison between the transmission parameter measured for an 8.5 mm long line section and one calculated by the FDTD method.

B. Applying the Method to the Analysis of the Optoelectronic Sampler

Behavior of the Propagation Line: To know the general behavior of the propagation line alone, the input signal is a pulse whose frequency bandwidth is approximately 10 GHz for −3 dB. The gradual evolution of the pulse waveform along this transmission line alone with taking the ohmic losses into account is shown on Fig. 5. The section of the line can be characterized by the S_{21} transmission factor. The dispersion of this line is not very high within the frequency range between 0 GHz and 20 GHz; however the ohmic losses induce a decrease of the magnitude of the current which is propagated along 4 cm, which is the length of the main line because of the temporal window.

In order to be able to compare the simulation and the experiment, we determine the transmission parameter between two planes 8.5 mm apart. In the theoretic modelization, the strip conductivity is equal to half the conductivity of gold and the thickness of the metal strip is 0.5 μm. On Fig. 6, the transmission parameter is measured for an 8.5 mm-long section using a Wiltron network analyzer and is compared to the transmission parameter calculated by the FDTD method. These plots are similar (they differ by 0.2 dB approximately). For the frequency bandwidth of this pulse, the skin effect does not cause any additional distortion.

The electromagnetic study presented above is the analysis of the propagation line alone, but in reality, the optoelectronic sampler consists of line propagation and sampling lines. So, we simulate the electromagnetic behavior of the propagation

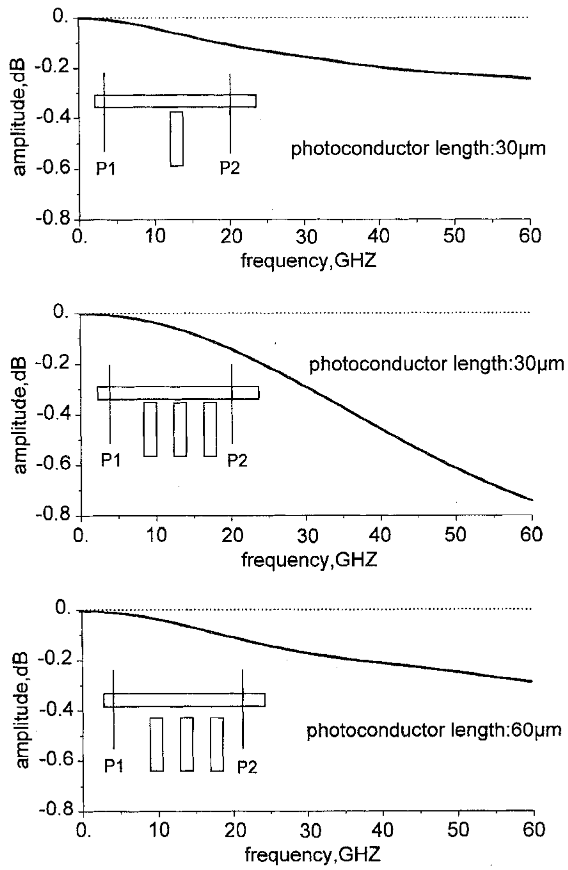

Fig. 7. Transmission parameters for various structures.

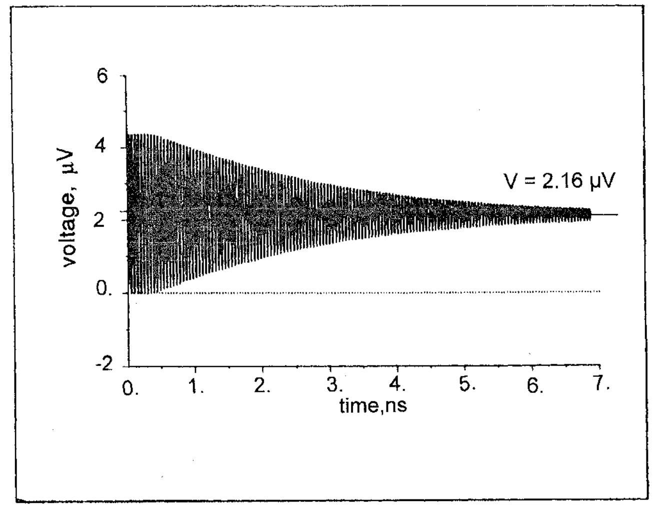

Fig. 8. Time voltage constant on the capacitor terminals.

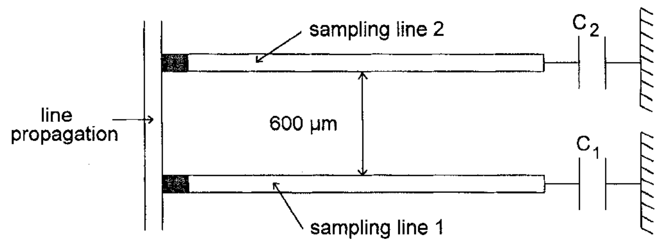

Fig. 9. Structure (two sampling lines) used to analyze the installation of steady state.

line in the presence of the sampling lines. For this study, the ohmic losses are not taken into account. The input signal bandwidth is larger than in the case of the previous signal used to study the propagation line alone. Fig. 7 shows the effect of the presence of three sampling lines on signal propagation along the principal line. For example, the transmission factor which characterizes an 8.5 mm long line section is −0, 65 dB for 50 GHz. These parameters are not very different from the transmission parameter in the presence of one sampling line multiplied by three. The distance between the propagation line and the sampling line is the length of the photoconductor. We simulate the propagation line in the presence of three sampling lines but the photoconductor is twice as long (60 μm). The transmission parameter is plotted in Fig. 7. As was foreseeable, the propagation line propagates without deformation ($|S_{21}| \# 0$). So a trade-off will have to be made between a sufficient photoconductor length to minimize the coupling effect and enough sensitiveness for photodetection.

Acquiring the Sampled Signal: The sampled signal is acquired thanks to the charge stored in the capacitors which are at the ends of the sampling lines. Charge storage is not instantaneous: the pulse will come and go several times along the sampling line before obtaining the signal samples. The installation of a steady state is simulated. The photoconducting element is polarized by an electric signal which is propagated along the principal line. Then, the photoconductor is illuminated and an ultra-fast Gaussian pulse (whose full width at half maximum is 3 ps and whose frequency bandwidth is about 100 GHz at −3 dB) is generated. This pulse is entirely distributed along the sampling line after illumination. The current is integrated in the time domain in order to find out the electric quantity which is photogenerated. This charge is proportional to the photoconductor biasing voltage. Several nanoseconds after illumination, the current is equal to zero, and the voltage is constant on the capacitor terminals (Fig. 8). The charge stored in the capacitor is equal to the product of the capacitance by the terminal constant voltage. The photogenerated charge is equal to the charge stored in the capacitor.

Then, we study the acquisition of two samples: we simulate the structure represented in Fig. 9. In order to know the effect of the coupling between the sampling lines on the charge stored in the capacitors, the photogenerated pulses are chosen with different shapes and different spectrums. The closeness of two sampling lines (therefore the coupling) distorts the pulses during the propagation along the sampling lines. However, the photogenerated charge on line 1 is equal to the charge on the C_1 capacitor terminals. This conclusion applies to line 2 as well. Finally, the coupling between the sampling lines does not affect sampling acquisition. The limit of the distance between two consecutive sampling lines depends only on the space distribution of the pulse generated by the photoconductor. These lines can deform the ultra-fast pulses because of dispersion. To obtain the sampled signal, the sampling line must be able to transmit the photogenerated

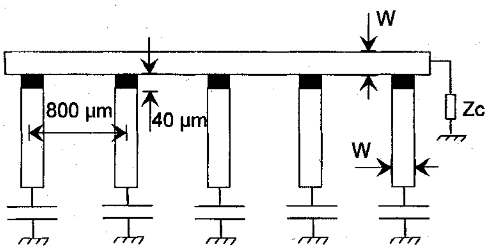

Fig. 10. Simulated sampler with five sampling lines.

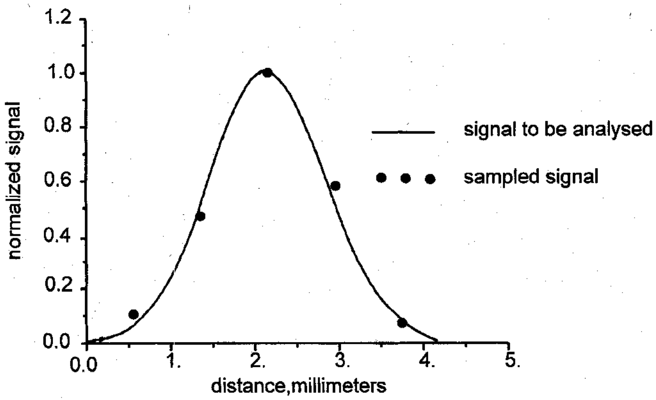

Fig. 11. Comparison between the signal to be analyzed and the sampled signal.

charges but it need not be able to transmit the energy of photogenerated ultra-fast pulses.

Optoelectronic Sampler Simulation: The full simulated device is a sampler with 5 sampling lines (Fig. 10). The characteristics of the microstrip line are

$$W = 120\,\mu\text{m}$$
$$H = 130\,\mu\text{m}$$
$$\text{Substrate : sapphire} \quad (\varepsilon_r = 9.8).$$

This sampler must analyze a signal whose full width is 40 ps and with a resolution of 7 ps.

Fig. 11 shows the space distribution of the current to be analyzed and the sampled signal. The similarity of the two curves shows the feasibility of such an optoelectronic sampler.

C. Applying the Method to the Analysis of the Autocorrelator

The aim of the electromagnetic study is to obtain an autocorrelator function similar to the measured function.

To do so, it is necessary to adapt the shape and amplitude of the conductivity, which enables us to simulate the response of the photoconductor. The characteristic of the photoconductor can be deduced from the simulated autocorrelation function. For this analysis, we choose a photoconductivity shape which depends on the carrier lifetime (coefficient τ_r), and the laser pulse (coefficient W_o and σ_{on})

$$\sigma(t) = \sigma_{on} \times g(t) \tag{3}$$

$$\text{with}\, g(t) = \frac{f(t)}{\max|f(t)|} \tag{4}$$

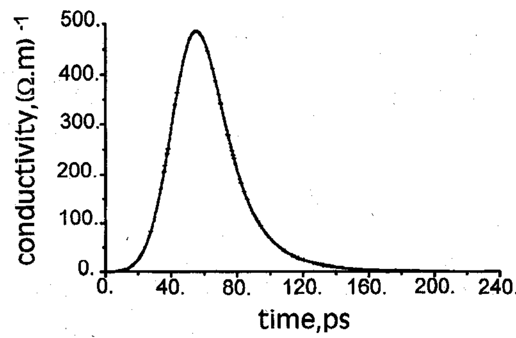

Fig. 12. Time conductivity selected for the simulation of the autocorrelation function.

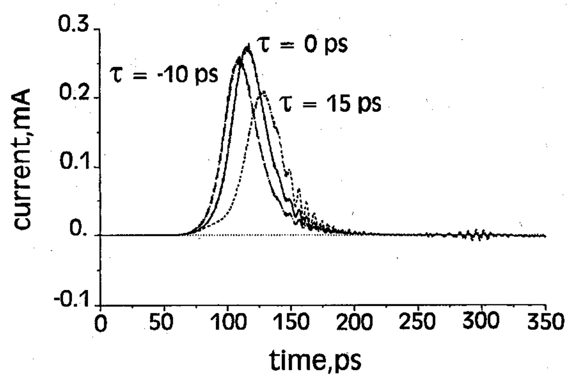

Fig. 13. Time currents for various delays.

$$f(t) = e^{-t/\tau_r} \int_0^t e^{\frac{-(t'-t_o)^2}{W_o^2}} e^{t'/\tau_r}\, dt. \tag{5}$$

The parameters that we make vary are the coefficients t_o and τ_r (to adapt the shape) and the coefficient σ_{on} (to adapt the amplitude).

The conductivity represented in Fig. 12 corresponds to $t_o = 44,5$ ps, $\tau_r = 17,5$ ps, $W_o = 18$ ps, and $\sigma_{on} = 485$ $(\Omega\text{m})^{-1}$. The pulse which is propagated along line L_3 due to the two photoconductors illumination for different delays is represented in Fig. 13. This pulse is obtained by subtracting the pulse calculated on line L_3 without photoconductor P2 illumination (an obscurity current is created by capacitance coupling) from the signal obtained under illumination. When the delay grows longer, the current form is more disturbed.

On line L_3, as previously, the charge which will be stored by the capacitor is equal to the charge contained in the photogenerated pulse which is propagated along line L_3. So, to build the autocorrelation function, the current has been integrated up to 245 ps, when the signal reflected by the capacitor occurred.

The calculated autocorrelation function corresponds to that of the measured function (Fig. 14). The characteristic deduced from the electromagnetic study shows that the resistance of the photoconductor under illumination is about 3 kΩ and the transient conductivity is deduced as well.

IV. CONCLUSION

A theoretical method is usually used for ultra high frequency structures (passive microwave circuits, antennas). This method

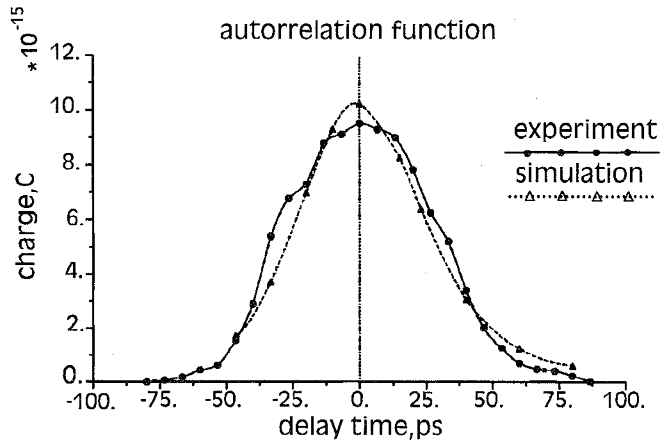

Fig. 14. Comparison between the autocorrelation function calculated by the FDTD method and one obtained by measurenment.

has been adapted to analyze the optoelectronic devices which propagate ultra fast transients (new microstrip feed and photoconductive switch). It has been applied here to the study of two systems: a sampler to show the feasibility of such a device and an autocorrelator to determine the photoconductor response.

Owing to recent advances in microwave and optic domains, it has today become possible to consider sampler for physical instrumentation with a better resolution. One of the challenges in this domain is to search for a structure suitable to the ultra fast pulse propagation (duration below picosecond). The applying of the method presented in this paper will advise us in the conception of new devices using other technologies (for example coplanar waveguide).

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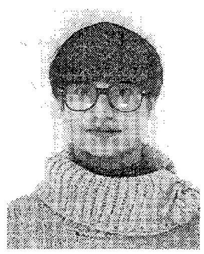
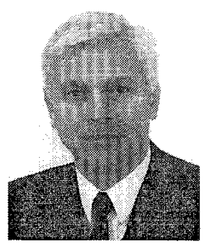


Lydie Armengaud was born in Lavaur, France, in 1969. She graduated with the "Diplome d'Etudes Approfondies" in electronics. She is now studying for her the Doctorate in Electronics from the University of Limoges, France, in the Laboratory of Electromagnetism of the Research Institute on Microwave and Optical Communications (IRCOM).

She is currently engaged in research on propagation problems on microstrip lines and optoelectronic devices.

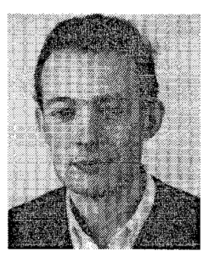
Michèle Lalande was born in Noth, France, in 1962. She received the Doctorate in Electronics from the University of Limoges, France, in 1986.

At present, she is a Lecturer, University Institute of Technology of Limoges (G.E.I.I. Department at Brive, France) and is a member of the Electromagnetics team of the Research Institute on Microwave and Optical Communications (IRCOM). She is engaged in research on propagation problems on microstrip and coplanar lines, and optoelectronic devices.



Bernard Jecko (M'91) was born in Trelissac, France, in 1944. He received the grade of science physic Doctor in Electronics from the University of Limoges, France, in 1979.

Now, he leads the Electromagnetic Team of the Research Institute on Microwave and Optical Communications (IRCOM). His fields of research are electromagnetic propagation, electromagnetic compatibility, antenna, radar cross section determination, and optoelectronic devices.



Nicolas Breuil was born at Saint Yrieix, France, in 1970. He graduated with the "Diplome d'Etudes Approfondies" in electronics from the University of Limoges. He is now studying for his Doctorate in Electronics from the University of Limoges, France, in the Optics team of the Research Institute on Microwave and Optical communications (IRCOM). He is engaged in research on picosecond pulses generation and correlation measurement by means of photoconductor switches and broadband characterization of propagation structures.

Alain Barthelemy, photograph and biography not available at the time of publication.

Marc Cuzin, was born in Paris in 1954. He received the degree in physics at the Institut National Polytechnique de Grenoble and a specialization in cristallography, and later, the Ph.D. degee at Genoble University in 1982 in the field of new detectors for medical radiology.

In charge of X-ray detector development in CEA/LETI, he has been working on fast scintillators and simulated luminescence since 1986. He then focused his activity in the field of direct detection in semiconductors, managing a team on fast detectors (GaAs, CdTe, diamond, etc.), and realizing picosecond detectors for monopulse measurement including optoelectoronic sampling techniques. He is the author of more than 25 papers or patents on photoconductors, and succeeded the "Habilitation à diriger des recherches" in 1991. He is now in charge of biomedical instrumentation activities in LETI.