MMIC-Calibrated Probing by CW Electrooptic Modulation

D. Le Quang, Didier. Erasme, and Bernard. Huyart

Abstract— **This paper describes an electrooptic probing technique using a cw semiconductor-laser beam associated with a fast photodetector. Besides its simplicity, this technique presents some advantages over the sampling one thanks to the presence of a Fabry-Perot effect, namely an enhancement of the electrooptic interaction and a simple solution to the calibration problem. The good validity of the calibration method allows the application of this technique to S-parameter measurements. The S-parameter determination, in modulus and in phase, of an industrial MMIC by the electrooptic method is reported and compared with direct network analyzer measurements.**

I. Introduction

WITHIN THE last few years, elctrooptic probing [1], [2] has been shown to be a powerful test method in various areas of physics, in particular the test of GaAs microwave integrated circuits. In this application, the goal is the measurement of the absolute voltage at various test points leading to the determination of S-parameters. A technique using a cw laser probing beam has shown a high measurement bandwidth and a good sensitivity [3]. Besides its simplicity and relatively low cost, it overcomes the calibration problem related to the nonuniformity of the reflections in the sample by making use of a Fabry-Perot effect within the substrate. Furthermore, the results are obtained directly in the frequency domain.

II. Experimental Method

The method consists in sending a cw optical beam through an electrooptic material where an electric field is present. The electric field induces crystal refractive indices variations (Pockels effect) which can be converted into a linear modulation (at the frequency of the electric field) of the intensity of the optical beam by the use of appropriated optical elements. In the case of GaAs microwave circuit probing, the electrooptic material can be the substrate itself and the electric field consists of the microwave signal. The intensity modulation at this microwave frequency can be measured, via a fast photodetector, on a spectrum or network analyzer. The signal at any node of the circuit can be measured in modulus and in phase in the frequency domain. The test frequency is limited only by the bandwidth of the photodiode. Commercially available photodiodes reach 45 GHz.

Manuscript received March 30, 1994; revised July 20, 1994.
The authors are with Département Communications, Ecole Nationale Supérieure des Télécommunications, 75634 Paris cedex 13.
IEEE Log Number 9410323.

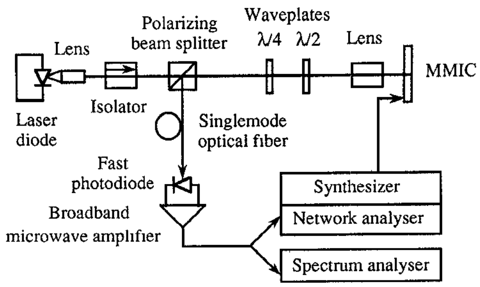


Fig. 1. Experimental setup.

The experimental setup is shown in Fig. 1. After passing through some polarizing elements, a 1.55-μm continuous laser beam is focused onto the back surface of the test circuit where the beam interacts with the fringing field of a microstrip line. After multiple reflections at the top and back surfaces of the substrate, the beam is sent to a photodetector via an optical fiber. The average power $I_{\rm av}$ received on the detector is given by the Airy function characteristic of the Fabry-Perot effect

$$I_{\rm av} = k\frac{I_{\rm inc}}{2}\frac{r^2+R^2+2rR\cos(4\pi nh/\lambda)}{1+r^2R^2+2rR\cos(4\pi nh/\lambda)} \quad (1)$$

where $I_{\rm inc}$ is the incident optical power on the circuit, n the refractive index of GaAs, h the substrate thickness, λ the laser wavelength, r and R the effective reflection coefficients of the top and back surfaces respectively (R includes the losses in the substrate), and k a factor denoting the power loss due to the optical elements and the injection into the fiber.

The electrooptic signal (for a cw signal on the microstrip) is given by

$$I_{\rm ppFP} = 2I_{\rm av}|\sin\Phi| \quad (2)$$

with

$$\Phi = \operatorname{arctg}\left\{\frac{R(1-r^2)\sin[\pi(4nh/\lambda + V_{\rm tp}/V_\pi)]}{r(1+R^2)+R(1+r^2)\cos[\pi(4nh/\lambda+V_{\rm tp}/V_\pi)]}\right\} - \operatorname{arctg}\left\{\frac{R(1-r^2)\sin[\pi(4nh/\lambda - V_{\rm tp}/V_\pi)]}{r(1+R^2)+R(1+r^2)\cos[\pi(4nh/\lambda-V_{\rm tp}/V_\pi)]}\right\} \quad (3)$$

where $I_{\rm ppFP}$ is the peak-to-peak value of the modulated intensity, $V_{\rm tp}$ the amplitude of the voltage at the test point, and V_π the half-wave voltage of the GaAs substrate defined by

$$V_\pi = \frac{\lambda}{2n^3r_{41}} \quad (4)$$

where r_{41} is the electrooptic coefficient of GaAs.

0018-9480/95$04.00

We have chosen an internal probe configuration where the electrooptic material is the GaAs substrate itself. This allows the measurements to be free from perturbations, which is important for obtaining the absolute measurements. Contrary to external probe systems where a complicated calibration technique is required to overcome the perturbation introduced by the external electrooptic crystal [4], a simple solution for the calibration is obtained in an internal probe system using a cw optical beam.

III. Calibration Procedure

In the electrooptic probing of MMIC's, a calibration method is necessary in order to determine the absolute voltage at various points of the circuits.

The calibration requires the determination of the local reflection coefficients r and R of the top and back substrate surfaces at the test point. It can be seen from (1)–(3) that, by using a tunable laser, these reflection coefficients can be determined from a pair of experimental curves $I_{\rm av}/I_{\rm inc}$ and $I_{\rm ppFP}/I_{\rm inc}$ versus the laser wavelength λ. This is obtained simply from two ratios

- the ratio between the maximum and minimum average optical powers

$$\frac{I_{\rm av\,max}}{I_{\rm av\,min}} = \left[\frac{(r+R)(1-rR)}{(r-R)(1+rR)}\right]^2 \tag{5}$$

- the ratio between the corresponding electrooptic signals, given by

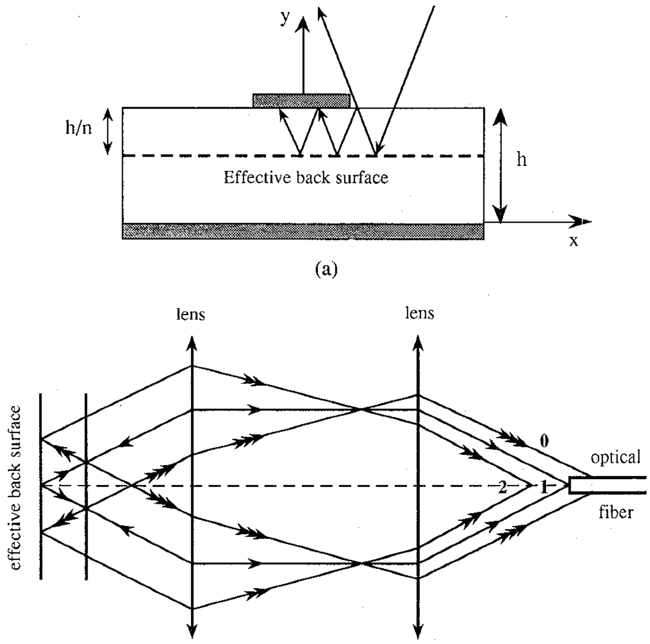
$$\frac{I_{\rm ppM}}{I_{\rm ppm}} = \frac{(r+R)(1-rR)^3}{(r-R)(1+rR)^3} \tag{6}$$

using the fact that the test point voltage $V_{\rm tp}$ is very small in comparison with V_π.

However, in the real system, these equations must be modified. Indeed, (5) and (6) are correct only when the laser beam is perfectly parallel when passing through the circuit and when reaching the photodiode. Now, there are the following two beam focalization mechanisms:

1) At the circuit (Fig. 2(a)): Since the incident beam must be focused just beside the microstrip line for a maximum electrooptic interaction and on the back substrate surface for obtaining a good spatial resolution, the 2nd, 3rd,... reflections from this surface are partly blocked by the stripline itself. These optical power losses can be calculated by using the theory of a Gaussian beam and by supposing that the line is large enough in comparison with the spot size of the focused beam.

2) At the entry of the fiber (Fig. 2(b)): In order to obtain a maximum detected electrooptic signal, the entry of the fiber must be positioned at the focal image of the first reflection. Then the following reflections are found to be focused farther and farther away from the fiber. These supplementary losses are difficult to determine in view of the small diameter of the fiber core (about 10 μm) and the geometry of the optical arrangement. In fact, if the circuit is not perfectly perpendicular to the incident beam, the conjugate images of the multiple reflections would not be on a same axis.



0 : optical reflection from the top substrate surface
1, 2,... : multiple reflections from the back surface

(b)

Fig. 2. Power losses for optical multiple reflections. (a) By the microstrip line. (b) At the entry of the fiber.

In order to take these losses into account, the multiple reflection powers have been chosen to be proportional to the terms of a geometric series whose ratio "a" is lower than 1. The equations (5) and (6) become

$$\frac{I_{\rm av\,max}}{I_{\rm av\,min}} = \left[\frac{(r+R[1-(1-a)r^2])(1-arR)}{(r-R[1-(1-a)r^2])(1+arR)}\right]^2 \tag{7}$$

$$\frac{I_{\rm ppM}}{I_{\rm ppm}} = \frac{(r+R[1-(1-a)r^2])(1-arR)^3}{(r-R[1-(1-a)r^2])(1+arR)^3}. \tag{8}$$

The reflection coefficient r of the top substrate surface can be easily determined from Fresnel's law. For industrial MMIC's whose top surface is generally covered by a protection dielectric layer, r can be calculated if the refractive index and the thickness of this layer are given.

Once the three quantities a, r, and R have been determined, the absolute voltage $V_{\rm tp}$ at the test point can be easily deduced from, for example, the ratio

$$\frac{I_{\rm ppM}}{I_{\rm av\,max}} = \frac{4\pi R(1-r^2)V_{\rm tp}}{(r+R[1-(1-a)r^2])(1+arR)V_\pi}. \tag{9}$$

IV. Fabry-Perot Enhancement of Electrooptic Interaction

The multiple reflections lead to an accumulation of electrooptic interaction during the multiple passages of the probe beam in the substrate. It can be seen that, by using a tunable laser, a wavelength that gives a constructive accumulation can be chosen, producing thus an enhancement of measurement sensitivity. This does not exist in any electrooptic sampling system because of the shortness of optical pulses.

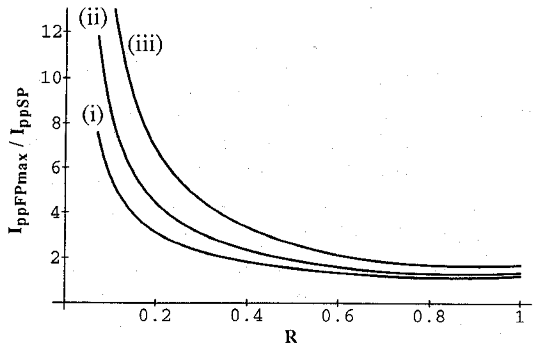


Fig. 3. Ratio $I_{\mathrm{ppFP}}/I_{\mathrm{ppSP}}$ of the maximum enhanced electrooptic interaction to that of the sampling technique as a function of the reflection coefficient R of the back substrate surface (i) $r = 0.4$; (ii) $r = 0.55$; and (iii) $r = 0.7$.

The electrooptic signal in a sampling system is given by

$$I_{\mathrm{ppSP}} = k\frac{4\pi}{\lambda}n^3 r_{41} R^2 (1-r^2)^2 I_{\mathrm{inc}} V_{\mathrm{tp}}. \tag{10}$$

Fig. 3 shows the ratio of the maximum electrooptic interaction enhanced by the Fabry-Perot effect to that of the sampling technique as a function of R by supposing that the incident optical power and the power loss are the same in both systems. The curves are plotted for several values of r and for $a = 0.5$. It can be seen that the enhancement becomes important when the reflectivity of the back surface is poor. This can be explained by the fact that in a sampling system, the electrooptic signal is due only to a single optical reflection on the back surface, whereas in a system using a continuous probe beam, multiple light passes and Fabry-Perot cavity tuning enhance the modulation. As shown in Fig. 3, the greater is r, the larger is the enhancement.

The fact that the optical power reflected by the top surface does participate to the electrooptic signal via the Fabry-Perot effect allows us to overcome another calibration problem encountered in a sampling system, that is the differentiation of the optical powers reflected by the top and the back surface.

V. Results and Discussions

A. With a Microstrip Line

Calibrated measurements: The first experiments have been carried out with a 50-Ω microstrip line deposited on a 500-μm-thick GaAs substrate whose top surface is simply a GaAs-air interface. The line was driven by a 6-GHz microwave signal and was terminated by a matched load. Fig. 4(a) represents the experimental variations of I_{av} and $I_{\mathrm{ppFP}} \cdot 10^4$, normalized to I_{inc}, against the laser wavelength λ. From these measurements and after the calibration procedure described above, we obtained: $a = 0.45$, $R = 0.32$, and $V_{\mathrm{tp}} = 0.56$ V. The theoretical curves using these numerical values show a good agreement between the theory and the experiment (Fig. 4(b)). The difference in the vertical axis in both figures is due to the optical power loss denoted by the factor k in (1). The difference in the horizontal axis is due to the translation of the curves in wavelength when the substrate thickness varies. The experimental curves appear to be shifted to the shorter wavelength side as if the wavelength scale has been

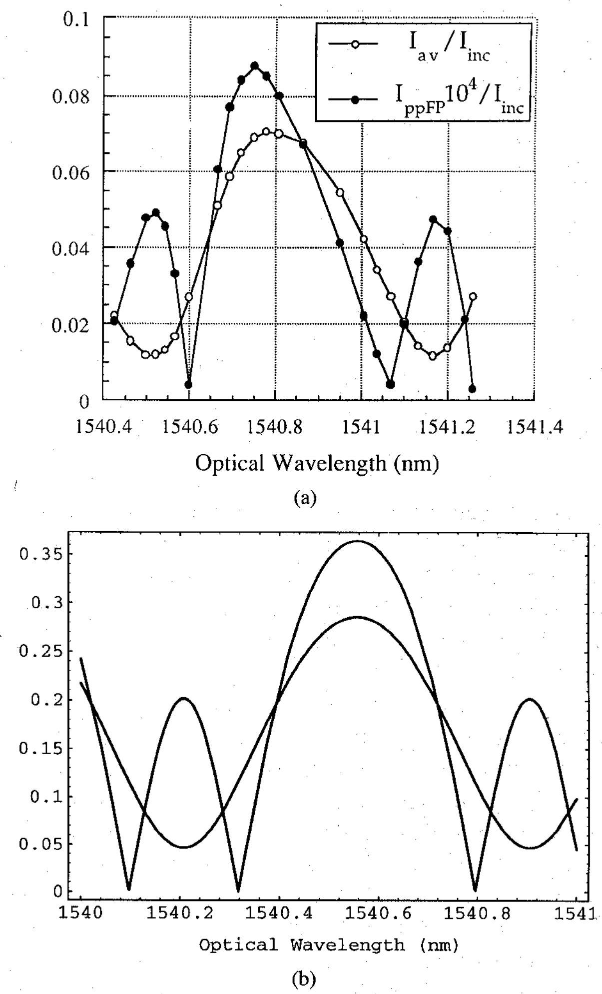


Fig. 4. Electrooptic effect in presence of Fabry-Perot effect. (a) Experimental. (b) Theoretical.

compressed in this region. This can be due to a bias in the calibration of the optical spectrum analyzer which was used to measure the laser wavelength, or to a temperature variation between the measurements.

It can be noted that if the theoretical curves of the non-modified Fabry-Perot model gives a good qualitative agreement with the experiment [3], the introduction of the corrective factor "a" makes the agreement quantitatively better, which allows us to calibrate the measurements.

The calibration method can be justified by the experimental measurements of well-known voltages. Fig. 5 shows the voltage distribution as a function of the distance from the center of the microstrip line. The solid curve represents the theoretical values calculated by the quasistatic method using the technique of separation of variables [5]. The points represent the electrooptic measurements after calibrations. The line was driven by a 5-GHz signal of 1-V amplitude.

Determination of the half-wave voltage V_π: It can be seen from (9) that the precision of the absolute voltage V_{tp} at the test point depends upon that of the half-wave voltage V_π. The value of this voltage is obtained with accuracy only when the refractive index n and, in particular, the electrooptic coefficient r_{41} of the GaAs are exactly known. There is not

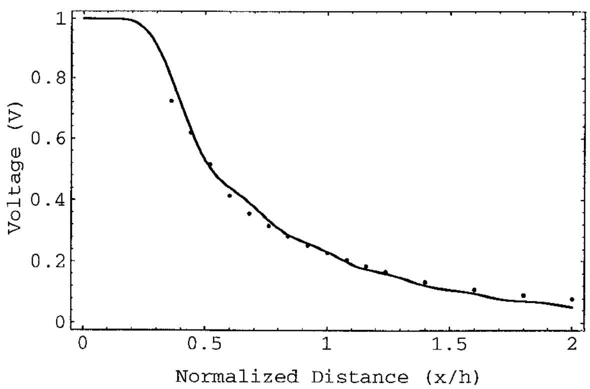


Fig. 5. Voltage distribution as a function of the distance (normalized to the substrate thickness h) from the center of a 50-Ω microstrip line.

a general agreement on the values of these parameters in the literature [6], [7]. In our calculations, we have taken n =3.4 and $r_{41} = 1.4 \cdot 10^{-12}$ m/V, which gives V_π =14 kV. The good agreement between the measurements and the simulation in Fig. 5 shows that this value for the half-wave voltage is a good estimation.

Sensitivity: Fig. 5 also shows that the voltage V_{tp} decreases rapidly when the laser spot moves away from the line. Only a good spatial resolution would lead to V_{tp} approaching the voltage V_0 on the line, resulting in an improved sensitivity. This resolution is determined by the spot sizes on the top and back surfaces of the substrate. The former is related to the geometry of the focused beam; the latter is limited by the diffractive nature of a Gaussian beam. It can be noticed that for a given focused beam, the best spatial resolution will be obtained when the beam waist is found not at the top substrate surface but at the back one. The spot size at the top surface is the smallest when the Rayleigh range of the focused beam is equal to the effective thickness h/n of the substrate. Its minimum diameter is given by

$$d_{\min} = 2\sqrt{2}w_0 = \sqrt{\frac{8h\lambda}{n\pi}} \tag{11}$$

where w_0 is the beam radius at the waist.

The minimum spot diameter is about 24.1 μm for h = 500 μm and about 10.8 μm for standard 100-μm-thick MMIC's.

With an optimal spot size and the Fabry-Perot enhancement of electrooptic interaction, a good sensitivity can be obtained. With our 500-μm-thick sample, a minimum detectable voltage of 1 mV/$\sqrt{}$ Hz (−40 dBm with RB = 10 Hz) for a 15-GHz measurement is obtained in spite of the modest power of our laser diode (5 mW). This good sensitivity is also due to the simplicity of the system which induces less power losses than many other ones. The optical power loss of the system is 12 dB for a maximum Fabry-Perot effect.

Finally, it must be noticed that the sensitivity depends strongly on the optical reflectivity of the back substrate surface. This reflectivity can vary greatly from circuit to circuit and even within a same substrate. According to the calibrations, the effective reflectivity R^2 of our 500-μm-thick sample lies between 0.1 and 0.25.

B. Six-Port Reflectometer MMIC

The test circuit is a six-port reflectometer designed in ENST for a 1.5–2 GHz bandwidth [8]. It is built up on a 1.5-mm^2-wide, 100-μm-thick GaAs chip whose top surface is covered by a 0.3-μm-thick silicon nitride layer. Its parameters S_{42} and S_{62}, measured on a network analyzer, are presented in Fig. 6(a). The voltages V_2, V_4, and V_6 on the input and output microstrip lines have been measured and calibrated by the electrooptic method. The ratios $(V_4/V_2)^2$ and $(V_6/V_2)^2$ are presented in dB in Fig. 6(b). It can be noticed that the curves exhibit the same characteristic as the network analyzer measurements. The discrepancy lies in the fact that both measurements are not quite equivalent. The electrooptic test does not include connexion losses. It does not either differentiate forward and backward propagating waves but measures the real local voltage.

The laser diode used is not a tunable laser but a DFB laser whose tunability is only 1 nm. This small tunability is not large enough for covering a Fabry-Perot period (in wavelength) of a 100-μm-thick substrate. In this case, the calibration parameters (a and R) are determined from the ratio between $I_{\text{av max}}$ (or $I_{\text{av min}}$) and the average optical power at any laser wavelength λ and from the ratio between the corresponding electrooptic signals.

In this experiment, a signal-to-noise ratio of 23 dB (optical) has been obtained for a 10-dBm power launched into the circuit. Thus, the minimum electrical power detected turns out to be −36 dBm.

As seen in Fig. 1, another interest of an electrooptic probe system operating in the frequency domain is that the data acquisitions can be made directly on a network analyzer. The voltage ratios are obtained by the subtraction of the curves for two test points as in Fig. 6(c). Differences in the reflection coefficient at both test points result in an offset of the reference level that can be easily taken into account.

Contrary to the magnitude measurements, the argument measurements of S-parameters by the electrooptic method are free from calibration problems and can be obtained directly on the network analyzer. Fig. 7(a) and 7(b) represents the phase of S_{42} and S_{62} measured directly on the network analyzer at the entry connections and by the electrooptic method at the test points corresponding to V_2, V_4, and V_6 mentioned above. The difference in slope comes from the difference in reference planes for both measurements. The agreement is very good.

VI. Conclusion

We have shown that an electrooptic test system based on a cw optical probe beam allows the calibration of the measurements, and therefore allows S-parameter determinations for microwave integrated circuits. The result reported shows a good agreement in the frequency behaviour with that obtained by a network analyzer. The calibration method is well validated, allowing us to determine experimentally the half-wave voltage of the GaAs. Finally, thanks to the Fabry-Perot enhancement of electrooptic effect, a good sensitivity has been obtained.

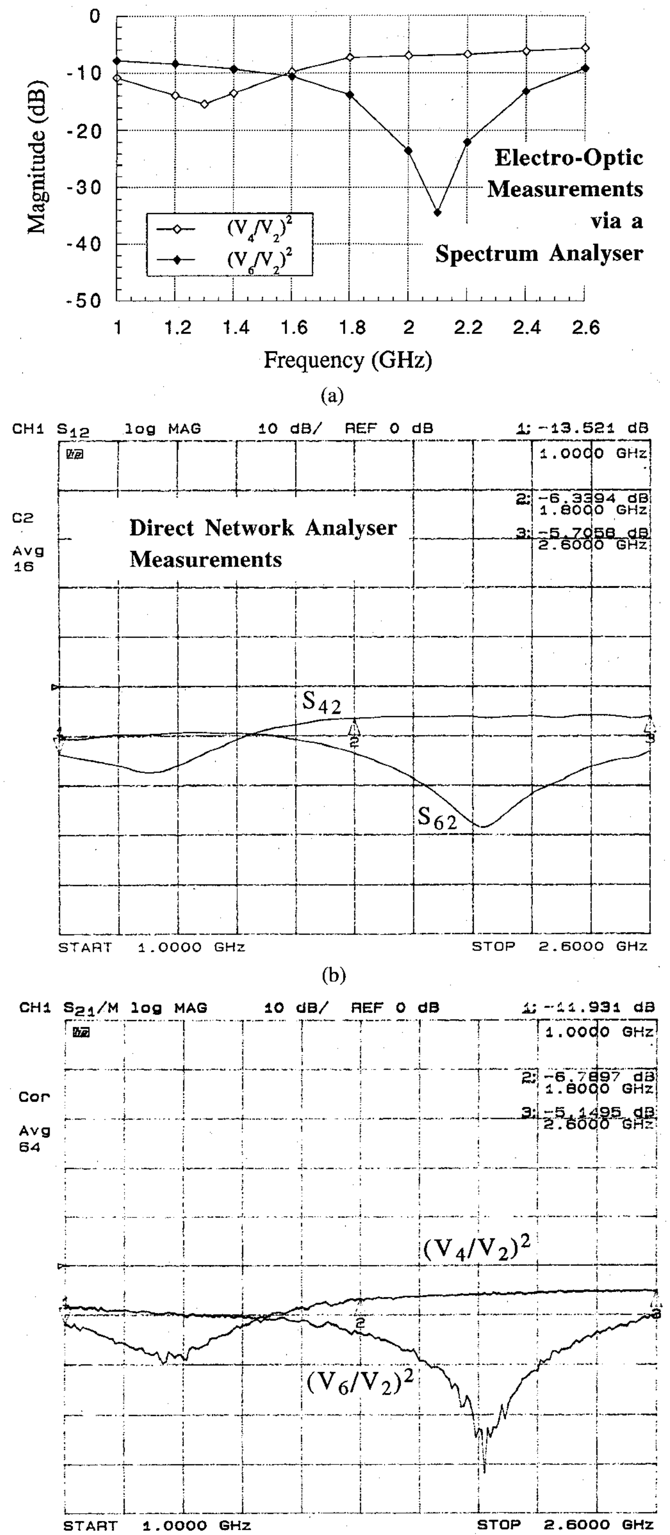


Fig. 6. S-parameters of a six-port reflectometer. (a) Direct network analyzer measurements. (b) Calibrated electrooptic measurements (via a spectrum analyzer). (c) Electrooptic measurements obtained on a network analyzer.

ACKNOWLEDGMENT

The authors would like to thank University College of London for the fabrication of the microstrip line and "L'entraide universitaire française" for the financial support of one of the authors.

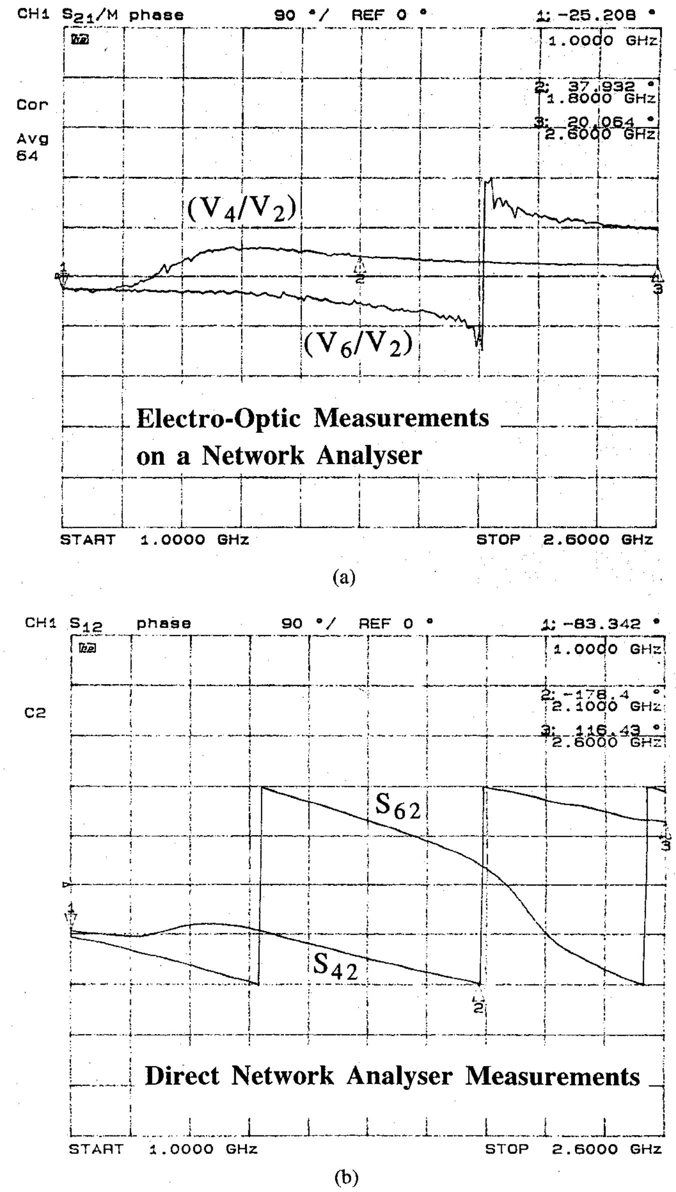
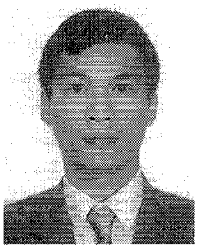


Fig. 7. Argument measurements of S-parameters. (a) Network analyzer measurements. (b) Electrooptic measurements.

REFERENCES

[1] B. H. Kolner and D. M. Bloom, "Electrooptic sampling in GaAs integrated circuits," *IEEE J. Quantum Electron.*, vol. QE-22, pp. 79–93, 1986.
[2] K. J. Weingarten, M. J. W. Rodwell, and D. M. Bloom, "Picosecond Optical Sampling of GaAs Integrated Circuits," *IEEE J. Quantum Electron.*, , vol. 24, pp. 198–220, 1988.
[3] D. Le Quang, D. Erasme, and B. Huyart, "Fabry-Perot enhanced real-time electrooptic probing of MMIC," *Electron. Lett.*, vol. 29, no. 5, pp. 498–499, Mar. 4, 1993.
[4] X. Wu, D. Conn, J. Song, and K. Nickerson, "Calibration of external electrooptic sampling using field simulation and system transfer function analysis," in *IEEE MTT-S Dig.*, pp. 221–224, 1993.
[5] D. M. Pozar, *Microwave Engineering*. Delham, MA: Addison-Wesley, pp. 187–190, 1990.
[6] A. Yariv and P. Yeh, *Optical Waves in Crystals: Propagation and Control of Laser Radiation.* New York: Wiley, 1984.
[7] S. Adachi, *Physical Properties of III-V Semiconductor Compounds.* New York: Wiley, 1992.
[8] E. Bergeault, B. Huyart, Y. Delisle, and R. G. Bosisio, "A MMIC six-port reflectometer," in *35th Midwest Symp. Circuits and Syst.*, Washington, DC., Aug. 1992.



Dai Le Quang was born in Saigon, Vietnam, on October 13, 1960. He received the B.S. degree in physics from Pedagogic University of Ho-Chi-Minh City in 1985. In 1988, he came to France, where he received the Diplôme d'Etudes Approfondies (DEA) in microelectronics in 1991.

Since that time, he has been a Ph.D. student at the Ecole Nationale Supérieure des Télécommunications (ENST), working on electrooptic probing of microwave integrated circuits.

Didier Erasme was born in Paris on December 19, 1960. In 1983 he received the Diplôme d'Ingénieur in physical engineering from L'Institut National Polytechnique de Grenoble. In July 1987, he completed a Ph.D. thesis on high-speed integrated-optic modulators at the University College, London.

After a 2-year post-doctoral work on electrooptic sampling at the University College, London, he joined Télécom Paris in 1989. He was appointed assistant professor in the optoelectronic group of the Ecole National Supérieure des Télécommunications (Télécom Paris). His current research interests are multiple-quantum-well modulators, semiconductor amplifiers, and electrooptic probing of integrated circuits.

Bernard Huyart was born in France in 1954. He received the degree of electrical engineer from the University of Lille (EUDIL) in 1977 and the Doctoral degree in physics from the National Superior Institute of Telecommunications (ENST) in 1986.

He joined Telecom Paris in 1987, where he is currently an assistant professor. His research interest is the field of microwave instrumentation development.