Systematic Determination of the Propagation Characteristics of Coplanar Lines on Semiconductor Substrate

Pierre Pribetich, Christophe Seguinot, and Patrick Kennis

Abstract —**A method allowing the systematic determination of the propagation characteristics of micron-size waveguides and overcoming the influence of feeding access discontinuities is presented. The complex propagation constant and characteristic impedance of a slow-wave Schottky contact coplanar line are determined in the 1 to 26 GHz frequency range under different dc bias conditions. Comparisons with transmission line model theoretical results show very good agreement, despite the large slow-wave factor, attenuation, and dispersion of the waveguide. The electric schemes of the feeding access discontinuities are also presented. This measurement technique, which has been tested under extreme conditions, should be easily extended to other transmission line structures.**

Keywords —**Slow-wave, coplanar line, microwave measurements, Schottky contact.**

I. Introduction

THE frequency behavior of distributed active devices such as IMPATT diodes and GaAs MESFET's can be investigated by considering electron–electromagnetic wave interactions. In fact such analysis is essentially developed for two-electrode devices by using simplifying assumptions [1], [2]. For three-electrode structures, such as MESFET's, because of the topology it seems more accurate to propose transmission line models. In this approach, two lossy transmission lines are considered, one relative to the gate mode, the other relative to the drain mode. In such modeling, passive electric and magnetic couplings between each line are first considered; then active coupling and transversal amplification are taken into account by a lumped equivalent transistor for each unit cell [3]. When such an approach is used, it is necessary to determine the propagation properties of the lossy lines as accurately as possible. So we must take into account the finite conductivity and the geometry of each electrode and the multilayered doped substrate.

The influence of these different parameters can be rigorously analyzed by using CPU time-consuming numerical methods. However, the use of analytical transmission line models is more suitable when using desktop computer CAD software. In this last case, the validity of the transmission line model must be defined by comparison with either numerical results or experimental data. This last way is considered in the present work.

Experimental characterization of propagation phenomena occurring in distributed devices, for example FET's, is very tedious. First, the equivalent gate and drain mode lines are usually very lossy, owing to the bulk losses in the substrate and to the metallic ones when electrode widths are of the order of a micron. Second, the discontinuities between the feeding access and the distributed device under test can be important and must be taken into account. Until now, only a few experimental results have been published for relatively low loss MIS lines for frequencies up to 15 GHz [4], [5]. Generally, when using classical calibration techniques, the discontinuity is first characterized independently of the lumped device under test. However, at high frequencies, from an electromagnetic point of view, it is more accurate to derive the electrical scheme of the discontinuity when it is connected to the distributed device under test. In fact, when the feeding access is connected to a lumped device, the discontinuity equivalent circuit may be different from that when it is connected to a distributed transmission line. With this in mind, we propose a method for the systematic determination of the phase constant, the attenuation, and the complex characteristic impedance of a transmission line. This method is successfully used to characterize a Schottky contact coplanar line of micron size from 1 to 26 GHz, under drastic conditions, that is,

- high value of slow-wave factor;
- significant attenuation;
- dispersive transmission line;
- strong mismatches between feeding line and device under test.

II. Principle of the Method and Tested Device

The geometry of the tested device is presented in Fig. 1. This circuit consists of a sequence of different coplanar lines (Fig. 1(a)). The 500-μm-long Schottky contact coplanar line is realized on a semiconducting mesa (cross

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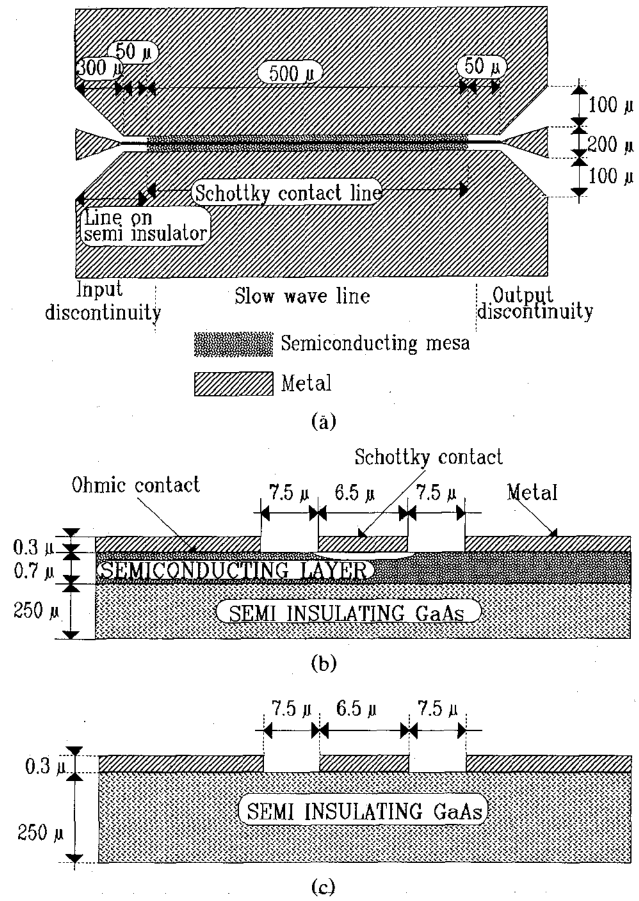

Fig. 1. Circuit layout: (a) top view of the tested device; (b) Schottky contact coplanar line cross section; (c) cross section of the coplanar line laid on semi-insulating layer.

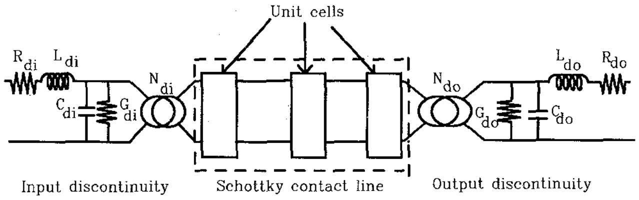

Fig. 2. Four-port network representation used for the simulation of the tested device.

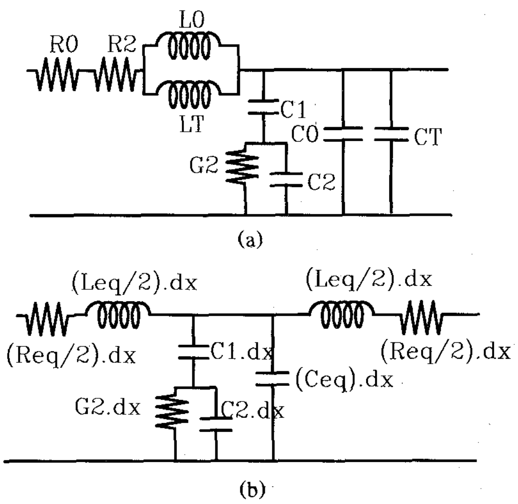

Fig. 3. Schottky contact coplanar line model: (a) transmission line analytical model; (b) electrical scheme of an elementary cell of length d_x used for the simulation.

section: Fig. 1(b)). This slow-wave line is inserted between two 50 Ω 50-μm-long lines laid on the semi-insulating layer of the substrate (Fig. 1(c)). Geometrical tapers are used to allow microwave probing of the device.

From a measurement point of view, the main difficulties in determining the propagation characteristics of the device under test are essentially due to the different discontinuities. The first is the discontinuity between the microwave probes and the coplanar line laid on semi-insulating material; the second is the one between the coplanar line on semi-insulating material and the Schottky contact coplanar line. Indeed, although the geometrical topologies for the two structures are similar, the electric and magnetic energy configurations are quite different for each line. One line propagates a quasi-TEM mode (semi-insulating coplanar line) while the line under test propagates a slow-wave mode with a high value of the slowing factor. This configuration induces a strong mismatch between the two structures.

In order to obtain a systematic characterization we need a precise and reliable experimental setup. In our case, we use an HP 8510 automatic network analyzer associated with Cascade Microtech microwave probes. In the measurement, the high attenuation and dispersive behavior of the line under test and the small length of each transition preclude easy characterization of each discontinuity by means of time-domain options. So we work in the frequency domain, taking into account the presence of the different mismatches. Furthermore, the theoretical analysis of the transitions shown in Fig. 1 is quite a complex problem. Thus it seems better, for engineering purposes, to determine an equivalent model for each discontinuity from the experimental data. To do this, we have used optimization procedures provided with the CAD software (ESSOF's Touchstone). First an electric scheme of the device under test is defined; then each element of this circuit is optimized so that the scattering parameters fit the measured data.

However, the microwave CAD software does not accommodate highly lossy coplanar lines with complex characteristic impedance, nor can it deal with the present discontinuities (version of March 15, 1987). So, we have modeled each discontinuity by a group of lumped elements. The lossy Schottky contact coplanar line is simulated by cascading unit cells (Fig. 2).

III. Schottky Contact Line Modeling

In this work we assume that only the even slow-wave mode is propagating ($E_Z(x) = E_Z(-x)$). The topology of each unit cell (Fig. 3(b)) is defined according to the transmission line model for Schottky contact coplanar line (Fig. 3(a)) defined in [6]. In this equivalent circuit C_T and

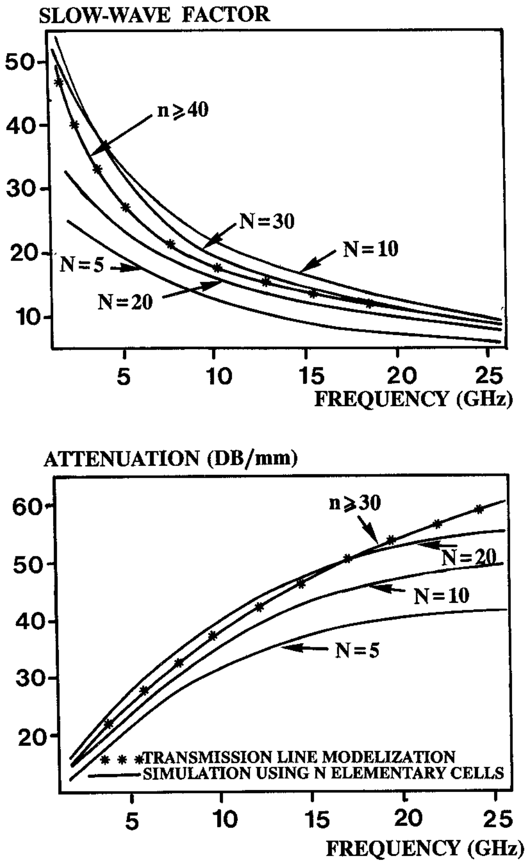

Fig. 4. Attenuation and slow wave factor of a Schottky contact coplanar line: comparison of two modelings: * * * transmission line modeling; —— simulation using N elementary cells, with line length = 500 μm (for $N > 40$ both simulations give the same results).

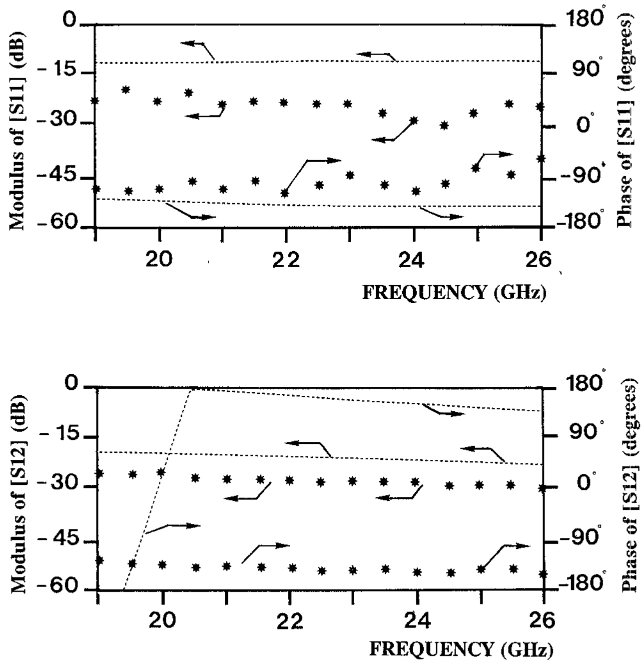

Fig. 5. Scattering parameters of tested device: * * * measurements; —— simulation obtained with the initial values (before optimization).

L_T account for the finite thickness of the metallization. C_1 is only relative to the depleted layer of the Schottky coplanar line and is simply calculated by using the one-dimension Shockley approximation, neglecting edge effects. L_0 and C_0 are respectively the inductance of the structure and the capacitance of the free space above the substrate. They are determined by conventional Schwarz-Christoffel conformal mapping [7]. Other elements are introduced to take into account the doped substrate: for low conductivity values, no slow-wave mode can propagate, so the contribution of the semiconductor medium is represented by G_2 and C_2. A series contribution of the bulk losses caused by the same layer is accounted for by R_2; this contribution is the dominant one when the mode is of the skin effect type. R_0 takes into account the metallic losses in the strips; it is calculated by using an approximation proposed by Fleming [8].

In the unit cells (Fig. 3(b)) series and parallel elements are grouped in equivalent terms such that

$$L_{eq} = (L_T L_0)/(L_T + L_0)$$

$$C_{eq} = C_0 + C_T$$

$$R_{eq} = R_2 + R_0.$$

Furthermore each element value is scaled to account for the finite length, d_x, of each cell:

$$d_x = L/N$$

where L is the total length of the Schottky contact line (500 μm) and N the number of cells taken into account. The unit cell is also made symmetric (Fig. 3(b)) so that the characteristic impedance introduced in the transmission line description is consistent with the definition used in four-port network theory.

Practical simulations of propagation phenomena require that a finite number of cascading cells be considered. So in a first step we must determine the minimum number of elementary cells ($N = L/d_x$). For the choice of d_x, the rule of thumb would be to take d_x much less than the guided wavelength for lossless lines. However, in our case, owing to the use of very dispersive and lossy structures, this criterion has been reconsidered. To do so, for typical physical and geometrical parameters, we have compared the frequency behavior of propagation characteristics when transmisssion line and cascaded cells simulations are used (Fig. 4). This comparative study shows that, in our case, at least 40 elementary cells are needed to obtain comparable slow-wave factor and attenuation values.

At this step the elementary cell elements of the Schottky contact line are initialized as follows:

- the resistance R_{eq} is evaluated by dc measurement;
- the capacitances C_1 and C_{eq} and the inductance L_{eq} are determined with the transmission line model;
- elements C_2 and G_2 have initial values so that they have no influence in the electrical scheme, $C_2 = 1/G_2 = 0$.

TABLE I
DISCONTINUITY ELECTRICAL SCHEME: INITIAL VALUES OF ELEMENTS

Element	Initial Value
RDE = RDS	0
LDE = LDS	0
CDE = CDS	0
1/GDE = 1/GDS	0
NDE = NDS	1

IV. DISCONTINUITY MODEL

In order to reduce the optimization time of the CAD program we used an electrical scheme (Fig. 2) with a global discontinuity including all the transitions from the probes (measurements system) to the line under test. In that scheme, we have thus grouped:

- the first discontinuity: probe to contact pads;
- the 50 Ω coplanar line on semi-insulating substrate;
- the second discontinuity: feeding coplanar line (50 Ω line) to Schottky contact coplanar line.

Obviously, if we were to use wide frequency band optimization, satisfying results could not be reached; this would be like obtaining average values on that frequency range. So we must divide the frequency range into several optimization bands in order to account for the frequency dependence of the discontinuity equivalent scheme. At this step, the main problem consists in determining the initial values of all the elements of electrical schemes for both the input and output discontinuities. These elements are initialized as presented in Table I, so that each discontinuity at input and output is transparent.

V. RESULTS

After determining the required number of elementary cells and choosing initial values, optimization procedure can be started. The value of each elements is optimized so that the simulated scattering parameters correspond as closely as possible to the experimental scattering parameters. It should be noted that the initial values have been chosen so that the initial scattering parameters of the simulated circuit are far from the measured data. As an example, Fig. 5 shows comparisons between frequency behavior of experimental scattering parameters and simulated ones obtained before optimization in the 19–26 GHz band. These curves exhibit strong discrepancies between experimental and theoretical values, particularly for the phase behavior. At this time, before optimization, the error evaluated by Touchstone software was about 2.6. This error has no absolute significance since it depends on the definition of the error function. It expresses the qualitative difference between the simulated and measured scattering parameters represented in Fig. 5. After optimization, this error is reduced to 0.073, indicating a much smaller difference between the scattering parameters measured and those simulated, as presented in Fig. 6.

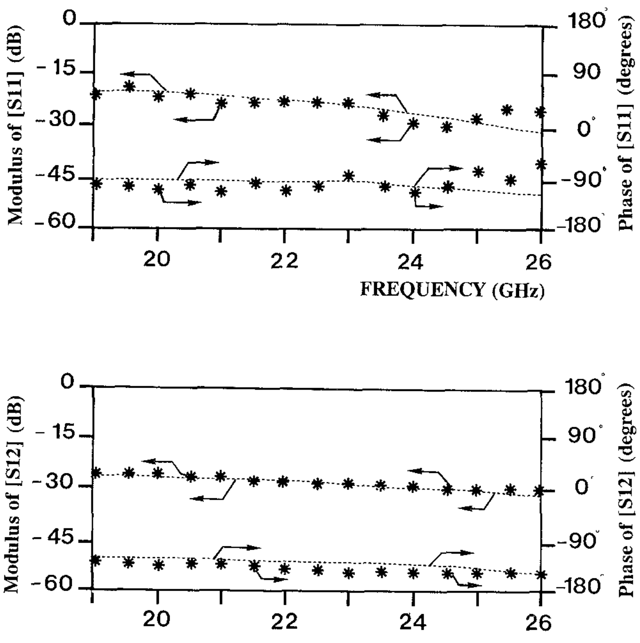

Fig. 6. Scattering parameters of tested device: * * * as measured; —— as simulated (after optimization).

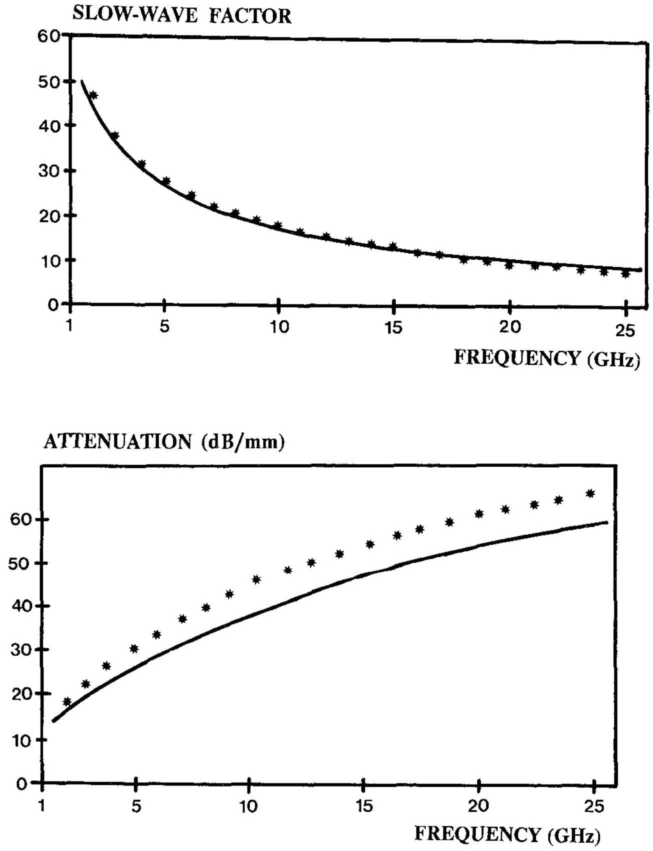

Fig. 7. Slow wave factor and attenuation of the Schottky contact coplanar line under −8 V dc bias: —— theoretical results obtained with the transmission line analytical model; * * * experimental characteristics derived from the measured scattering parameters.

TABLE II
VALUES OF ELEMENTS BEFORE AND AFTER OPTIMIZATION
(SCHOTTKY CONTACT dc BIAS: −8 V; FREQUENCY RANGE: 19–26 GHz)

Element	Initial Value	Final Value
$R_{eq}/2$ (Ω/cm)	1800	2246
C_1 (pF/cm)	13.9	14.79
C_{eq} (pF/cm)	1.2	0.16
$L_{eq}/2$ (nH/cm)	2.47	2.9
$1/G_2$ (Ω/cm)	0	0.5
C_2 (pF/cm)	0	1.66

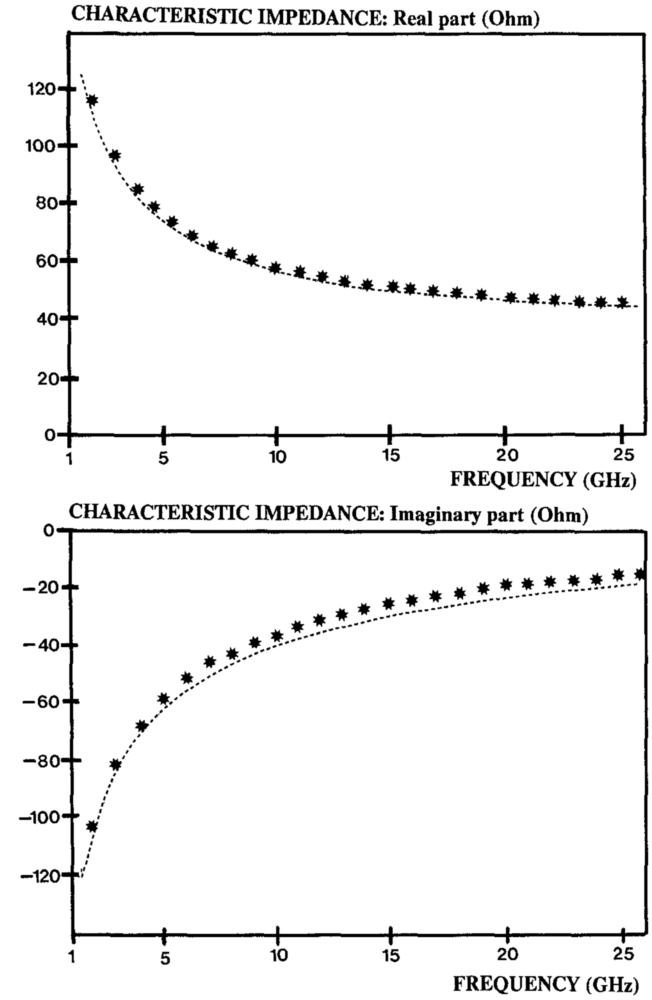

Fig. 8. Complex characteristic impedance of the Schottky contact coplanar line under −8 V dc bias: —— theoretical results obtained with the transmission line analytical model; * * * experimental characteristics derived from the measured scattering parameters.

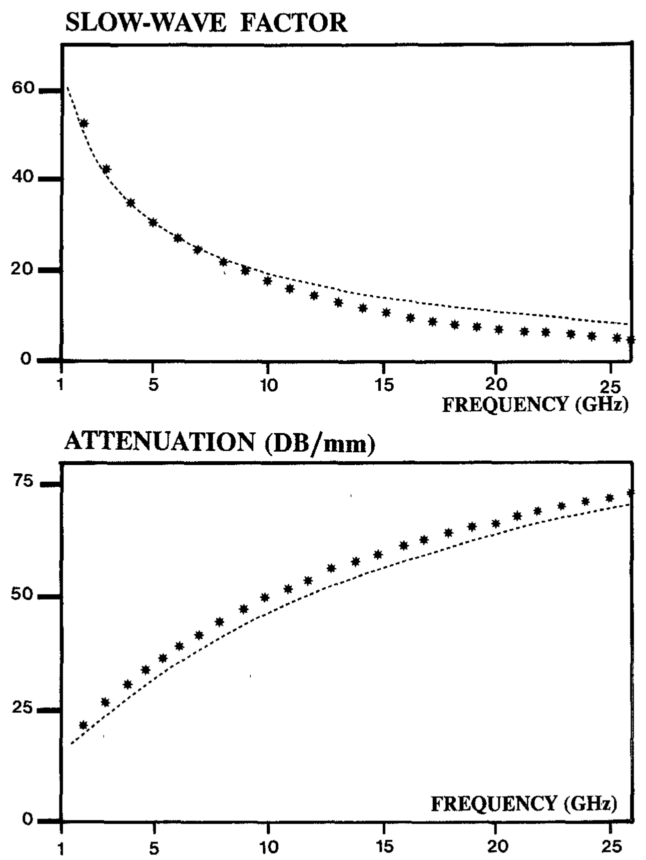

Fig. 9. Slow-wave factor and attenuation of the Schottky contact coplanar line under −4 dc bias: —— theoretical results obtained with the transmission line analytical model; * * * experimental characteristics derived from the measured scattering parameters.

Table II summarizes the element values of the Schottky contact coplanar lines obtained under −8 V dc bias conditions in the 19–26 GHz frequency range.

By using this method in a different frequency band, we have derived the propagation characteristics of the Schottky contact coplanar line from 1 to 26 GHz. By way of example, we present a comparison between the simulated results derived from experiments and the theoretical results obtained with our analytical transmission line model, both for the slow-wave factor and the attenuation (Fig. 7) and for the complex characteristic impedance (Fig. 8). We can observe very good accuracy between these different results. Only a few discrepancies appear for the attenuation (Fig. 7), with a difference in the worst case of about 10%.

By using the present method, we have also characterized the line under −4 V dc bias conditions. Once again, very good agreement is obtained both for the slow-wave factor and the attenuation (Fig. 9) and for the complex characteristic impedance (Fig. 10). We note that these satisfying comparisons have been obtained in spite of the drastic measurements conditions arising from the high value of the slow-wave factor (up to 60) and the attenuation (up to 70 dB/mm).

We also summarize (Table III) the input and output discontinuity element values. These results have been

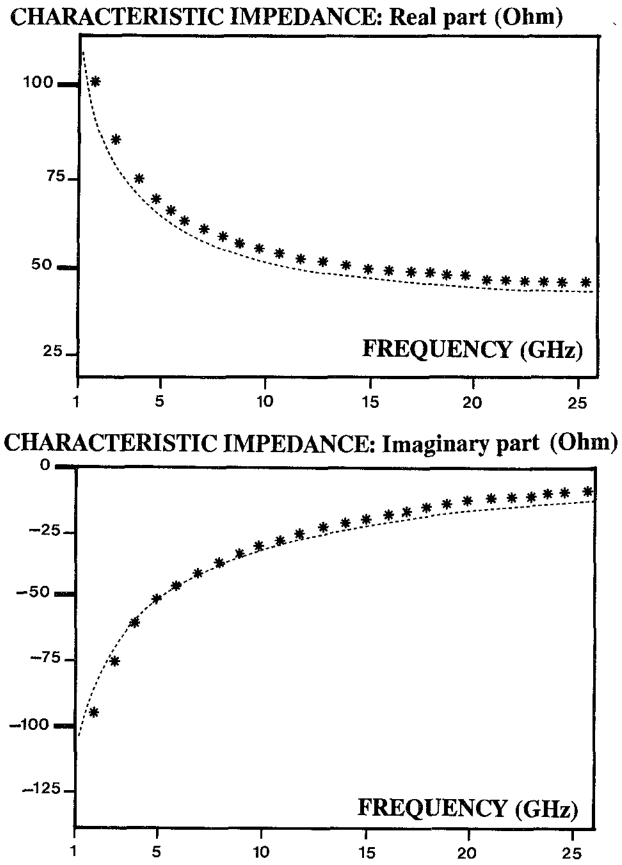

Fig. 10. Complex characteristic impedance of the Schottky contact coplanar line under −4 V dc bias: —— theoretical results obtained with the transmission line analytical model; * * * experimental characteristics derived from the measured scattering parameters.

TABLE III
ELECTRICAL SCHEME FOR INPUT AND OUTPUT DISCONTINUITIES OBTAINED IN THE 19–26 GHz FREQUENCY BAND UNDER −4 AND −8 V dc BIAS

dc Bias (Volt)	$V=-8$		$V=-4$	
Port	Input	Output	Input	Output
R_d (Ω)	2.78	0.47	2.99	0.89
L_d (pH)	80.27	52.75	110.3	42
C_{DS} (fF)	7	0.2	0.7	1
N_d	0.93	0.92	0.75	1.19

obtained in the 19 to 26 GHz frequency range, under −4 V and −8 V dc bias conditions. These complex discontinuities have been analyzed as a whole and in a reduced frequency band. Therefore we cannot attribute a physical significance to each element of the discontinuity scheme. Nevertheless, each electrical scheme conveys the overall electrical influence of a whole discontinuity.

The parallel conductance (G_d) was found to be negligible in all cases and is not reported in Table III. At a first observation, the variations of capacitance C_d with dc bias seem important. However this parallel capacitance (C_d) has only a reduced influence compared with that of other elements. So to a first-order approximation, the electrical influence of each discontinuity is conveyed by three elements: R_d, L_d, and N_d. The relatively high values of series elements point out the important influence of the discontinuity between the feeding probes and the Schottky contact line under test.

VI. CONCLUSION

An original technique has been presented for the experimental determination of micron-size coplanar waveguide propagation characteristics. The transmission line complex propagation constant and complex characteristic impedance have been determined systematically and directly from the measured scattering parameters of a section of line, overcoming the different electromagnetic discontinuities. The measurements have been made with microwave "on wafer" probes with an automatic network analyzer. Then, using readily available CAD software (EESOF's Touchstone), we have derived the different electromagnetic parameters of the investigated structure, which in the present case was a Schottky contact coplanar line. Very good agreement has been obtained between the theoretical results calculated with an analytical transmission line model and experimental ones. This methodology offers certain advantages in that we obtain both the experimental propagation characteristics of the transmission line and the electric scheme of the feeding discontinuities. This measurement technique has been tested under extreme conditions, for a line with a high slowing factor and very strong mismatches; it should be easily extended to other transmission lines structures.

REFERENCES

[1] Y. Fukuoka and T. Itoh, "Field analysis of a millimeter wave GaAs double drift IMPATT diode in the travelling wave mode," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 216–222, Mar. 1985.
[2] M. Franz and J. B. Beyer, "The travelling wave IMPATT diode," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 861–865, Nov. 1978.
[3] W. Heinrich, "Distributed equivalent circuit model for travelling wave FET design," *IEEE Trans. Microwave Theory Tech.*, vol. MTT 35, pp. 487–491, May 1987.
[4] V. M. Hietala, Y. R. Kwon, and K. S. Champlin, "Low loss slow wave propagation along a microstructure transmission line on a silicon surface," *Electron Lett.*, vol. 22, pp. 755–756, July 1986.
[5] Y. R. Kwon, V. M. Hietala, and K. S. Champlin, "Quasi TEM analysis of 'slow wave' mode propagation on coplanar microstructures MIS transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 545–551, June 1987.
[6] P. Pribetich, C. Seguinot, and P. Kennis, "Propagation characteristics of coplanar transmission lines laid on semiconductor substrates," *Alta Frequenza*, vol. VII, no. 7, pp. 417–430, Sept. 1988.
[7] C. P. Wen, "Coplanar waveguide: A surface strip transmission line suitable for nonreciprocal gyromagnetic applications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 1087–1091, Dec. 1977.
[8] P. L. Fleming, T. Smith, H. E. Carlson, and W. A. Cox, "GaAs SAMP devices for KU band switching," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 1032–1035, Dec. 1979.

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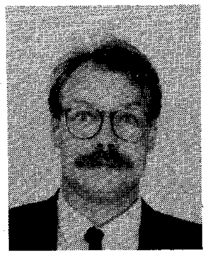

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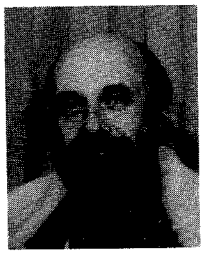

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