November 1981 through May 1982, and at Duisburg University, Duisburg, West Germany, from June through September 1982. His current research activities are in the areas of microwave circuits and devices, electromagnetic fields, and solid-state devices.

Dr. Tripathi is a member of Eta Kappa Nu and Sigma Xi.

Ingo Wolff (M'75) was born on September 27, 1938, in Köslin/Pommern, Germany. He received the Dipl.-Ing degree in electrical engineering, the Dr.-Ing degree, and the Habilitation degree, all from the Technical University of Aachen, Aachen, West Germany, in 1964, 1967, and 1970, respectively.

After two years time as an Apl. Professor for high-frequency techniques, he became a full Professor for electromagnetic field theory at the University of Duisburg, Duisburg, West Germany. He leads an institute where research work in all areas of microwave and millimeter-wave theory and techniques is done. His main areas of research at the moment are CAD and technologies of microwave integrated circuits, millimeter-wave integrated circuits, planar antennas, and material parameter measurements at microwave frequencies.

Characteristics of Metal–Insulator–Semiconductor Coplanar Waveguides for Monolithic Microwave Circuits

ROBERTO SORRENTINO, MEMBER, IEEE, GIORGIO LEUZZI, AND AGNÈS SILBERMANN

Abstract—**Using a full-wave mode-matching technique, an extensive analysis is presented of the slow-wave factor, attenuation, and characteristic impedance of a metal–insulator–semiconductor coplanar waveguide (MISCPW) as functions of the various structural parameters. Design criteria are given for low-attenuation slow-wave propagation. By a proper optimization of the structure, performances comparable with or even better than those of alternative structures proposed in the literature are theoretically predicted.**

I. Introduction

MONOLITHIC MICROWAVE integrated circuits, using both Si and GaAs technologies, have an increasing impact in a number of applications because of higher reliability, reproducibility, and potentially lower costs [1]. It has already been pointed out that accurate analysis techniques are required in order to reduce necessity for trimming, which is more difficult than for hybrid integrated circuits. Even in this case, however, full-wave analyses are necessary to study propagation effects in active devices [2]. Gigabit logic is another area where propagation effects have to be accounted for through the use of accurate theoretical analyses [3].

Slow-wave propagation in metal–insulator–semiconductor and Schottky-contact planar transmission lines has been both experimentally observed and theoretically explained from different points of view [3]–[10]. The slow-wave properties of such transmission lines can be used to reduce the dimensions and cost of distributed elements to realize delay lines or, when Schottky-contact lines are used, for variable phase shifters, voltage-tunable filters, etc.

A drawback of these slow-wave structures is the loss associated with the semiconducting layer. As an example, the GaAs metal–insulator–semiconductor coplanar waveguide (MISCPW) experimented by Hasegawa and his coworkers [6], [11] presented an attenuation greater than 1 dB/mm, with a slowing factor of about 30 at the frequency of 1 GHz. Since losses and slow-wave effects depend on the distribution of the electromagnetic field inside the various regions of the structure, accurate analyses are required to determine the most favorable conditions for the practical use of such transmission lines.

An extensive study of the properties of MISCPW, based on a full-wave technique, is presented in this paper. The influence of the various structural parameters on the characteristics of the structure is investigated, together with the effect of the addition of a back conducting plane, which

Manuscript received July 22, 1983; revised November 10, 1983. This work was supported in part by the Consiglio Nazionale delle Ricerche (CNR), Italy.

R. Sorrentino is with the Dipartimento di Elettronica, Università di Roma La Sapienza, Via Eudossiana 18, Rome, Italy.

G. Leuzzi is with the Dipartimento di Elettronica, Università di Roma Tor Vergata, Via O. Raimondo, Rome, Italy.

A. Silbermann is with Elettronica S.P.A., Via Tiburtina, Rome, Italy.

0018-9480/84/0400-0410$01.00 ©1984 IEEE

can be used for increasing the mechanical strength of the circuits [12]. Conductor loss has not been included in the analysis since it is generally negligible with respect to semiconductor loss. The method of analysis is basically a classical mode-matching technique [10]. For clarity of presentation, it is briefly described in the next section, but the analytical details are omitted.

The computed results are presented and discussed in the third section. They indicate that, by properly choosing its parameters, the MISCPW is capable of slow-wave low-loss propagation with characteristics comparable to or better than those of alternative structures proposed for the same type of applications [11].

II. Method of Analysis

Fig. 1 shows a sketch of the MISCPW. The analysis of the structure can be reduced to that of a discontinuity problem in a parallel-plate waveguide by inserting two longitudinal electric or magnetic planes perpendicular to the substrate, sufficiently apart from the slots. The effect of these auxilliary planes is expected to be negligible since the EM field is normally confined to the proximity of the slots. Because of symmetry, a further magnetic longitudinal wall can be placed at the center of the strip conductor for analyzing the dominant even mode of the CPW. The geometry of the reduced structure is shown in Fig. 2. As viewed in the y-direction, it appears as a parallel-plate waveguide (with plates of electric or magnetic type at $x=0$ and $x=a$) which is loaded with three (lossy) slabs and a metallic iris of finite thickness. The analysis can be performed using a classical mode-matching technique. Assuming a z-dependence as $\exp(-\gamma z)$, the EM field is expanded in each homogeneous section $(i=1,2,\cdots,6)$ in terms of $TE^{(y)}$ and $TM^{(y)}$ modes of the parallel-plate waveguide; the boundary conditions at infinity and at $y=y_i$ $(i=1,2,\cdots,5)$, through the use of the orthogonality properties of the modes, lead to a homogeneous system of equations in the expansion coefficients. For nontrivial solutions the coefficient matrix must be singular; this leads to a transcendental equation in the complex propagation constant.

The system of equations can be manipulated so that the only unknowns are the wave amplitudes in region 5. The result is a small number of equations (typically less than 12), which requires little computing time. The roots of the characteristic equation have been computed using the ZEPLS program [13]. Once a value of γ has been computed, the EM field expansion coefficients are obtained as the eigensolutions of the homogeneous system. From this, any other quantity relevant to the mode of propagation can be computed, such as field distribution, power density, and characteristic impedance. With regard to the last quantity, the following definition has been adopted:

$$Z_0=|V|^2/(2P^*)$$

where V is the voltage between the strip conductor and ground, and P the complex power flowing through the cross section of the structure.

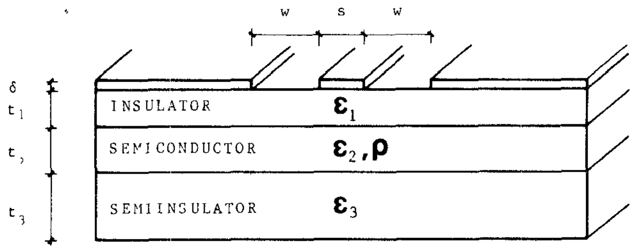

Fig. 1. The MISCPW.

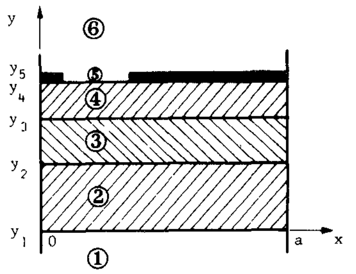

Fig 2. Reduced geometry of the MISCPW for analysis purposes.

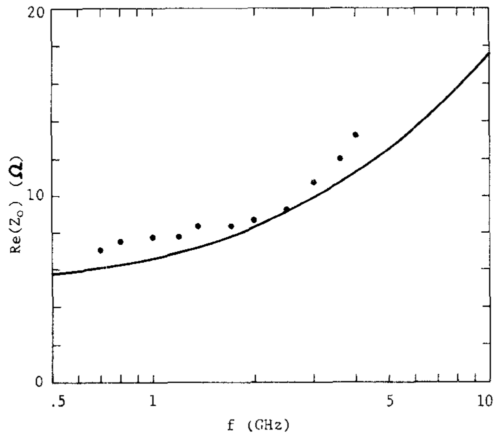

Fig. 3. Frequency behavior of the real part of the characteristic impedance of Hasegawa's MISCPW. Dots represent experiment [6].

III. Results

In a preliminary work [10], the agreement was demonstrated between the slow-wave factors and attenuations computed by the present method and the measurements performed by Hasegawa and coworkers [6], [11] on a specific MISCPW on GaAs substrate. (With reference to Fig. 1, the parameters of this structure were: $s=0.1$ mm, $w=0.45$ mm, $t_1=0.4$ μm, $t_2=3.0$ μm, $\epsilon_1=8.5$, $\epsilon_2=\epsilon_3=13.1$, $\rho=5.5$ 10^{-5} $\Omega\cdot$m.) As shown in Fig. 3, a similar agreement has been obtained with regard to the characteristic impedance of the same structure. Such results suggest the suitability of the above-described technique for an extensive analysis of the properties of MISCPW. It should be observed that the behavior of a MISCPW depends on a number of quantities, namely: the frequency f, the width s of the strip conductor, the distance $s+2w$ between the ground planes, the thickness δ of the metallization, the thicknesses t_i $(i=1,2,3)$ of the substrate layers, the doping level n_d, or the resistivity ρ of the semiconducting layer. $\epsilon_1, \epsilon_2, \epsilon_3$ have not been accounted for, as we suppose the substrate material is given. It is clearly very difficult to work with such a high number (eight) of parameters. We have observed, however, that the thickness of the metallization has a nonsubstantial or even negligible effect; moreover, as long as the semiinsulating layer thickness is large, as in the case previously analyzed, its influence is negligible too. Since we are interested in singling out the conditions for low-loss propagation, the resistivity of the semiconducting layer can be fixed at the value corresponding approximately to the minimum attenuation [10]. We have found, in fact, that this value is slightly sensitive to the structural parameters. Finally, because of the scaling properties of Maxwell's equations, the results obtained for a given structure at a frequency, say, of 1 GHz can be easily extended to another structure with all linear dimensions and semiconductor resistivity scaled by a factor of $1/\kappa$ at the frequency of κ GHz.

We started our computations examining the MISCPW experimented by Hasegawa [6]. As previously shown [10], at $f=1$ GHz, this structure has a minimum theoretical attenuation of about 2 dB/mm for a semiconductor resistivity ρ of about 1.3 10^{-5} $\Omega \cdot$m, corresponding to a doping level $n_d = 6\ 10^{17}$ cm^{-3} (assuming a GaAs electron mobility of 8000 cm^2/Vs). For about the same value of ρ, the slow-wave factor λ_0/λ_g has a maximum of about 40. (λ_0 is the free-space wavelength and λ_g the MISCPW dominant mode wavelength.)

A. *Effect of Shape Parameters*

Using such an optimum value of ρ, we have computed the results shown in Fig. 4, where α and λ_0/λ_g are plotted at the frequency of 1 GHz against the shape parameters

$$q = t_1/(t_1+t_2) \qquad r = s/(s+2w)$$

which characterize the substrate and metallization geometries, respectively. The distance $s+2w$ between the ground planes and the thickness t_1+t_2 of the insulating plus semiconducting layers have been kept equal to those of Hasegawa's structure.

It is observed that, while the attenuation has a marked dependence on both q and r, the slow-wave factor is slightly affected by the geometry of the metallization (r), as it is mainly influenced by the geometry of the substrate (q). As the semiconducting layer thickness t_2 is reduced from ~ 3 μm ($q=0.1$) to ~ 0.3 μm ($q=0.9$), the corresponding slowing factor is reduced from values greater than 40 to about 15. The attenuation, on the contrary, decreases with q down to a minimum for $q \sim 0.75$; as q approaches unity, α has first a local maximum, which is sharper with the smaller r, then rapidly decreases to zero as the semiconducting layer thickness becomes zero ($q=1$).

Very high slowing factors (>40) can be obtained for low q's, thus thicker semiconducting layers, but at the price of higher attenuations; it can be observed that the increased attenuation is generally not compensated for by the possible reduction of the dimensions of the circuits due to the higher value of λ_0/λ_g. For example, for $r=0.2$ and q varying from 0.5 to 0.1, λ_0/λ_g increases by a factor of

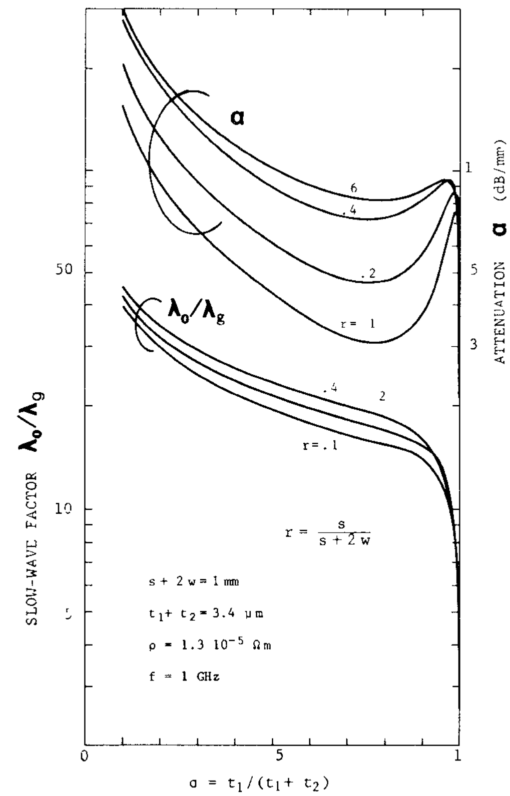

Fig. 4. Attenuation and slow-wave factor of MISCPW. $f=1$ GHz, $\rho = 1.3\ 10^{-5}\ \Omega\cdot$m, $s+2w=1$ mm, $\delta=1$ μm, $t_1+t_2=3.4$ μm, $t_3=0.997$ mm, $\epsilon_1=8.5$, and $\epsilon_2=\epsilon_3=13.1$.

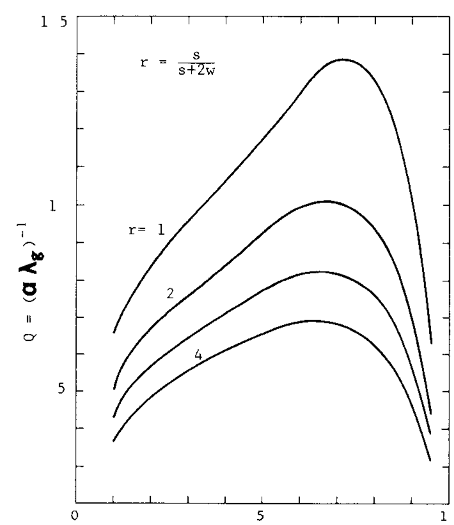

Fig. 5. Quality factor of the MISCPW of Fig. 4.

~ 2, while α increases by a factor of ~ 3. In order to get a quantitative comparison between structures with different slowing factors and different attenuations, we can use as a quality factor the parameter

$$Q = (\alpha\lambda_g)^{-1}.$$

The Q behavior computed from the data in Fig. 4 is shown in Fig. 5. These figures indicate that, in order to obtain lower attenuations with still considerable slowing factors, it

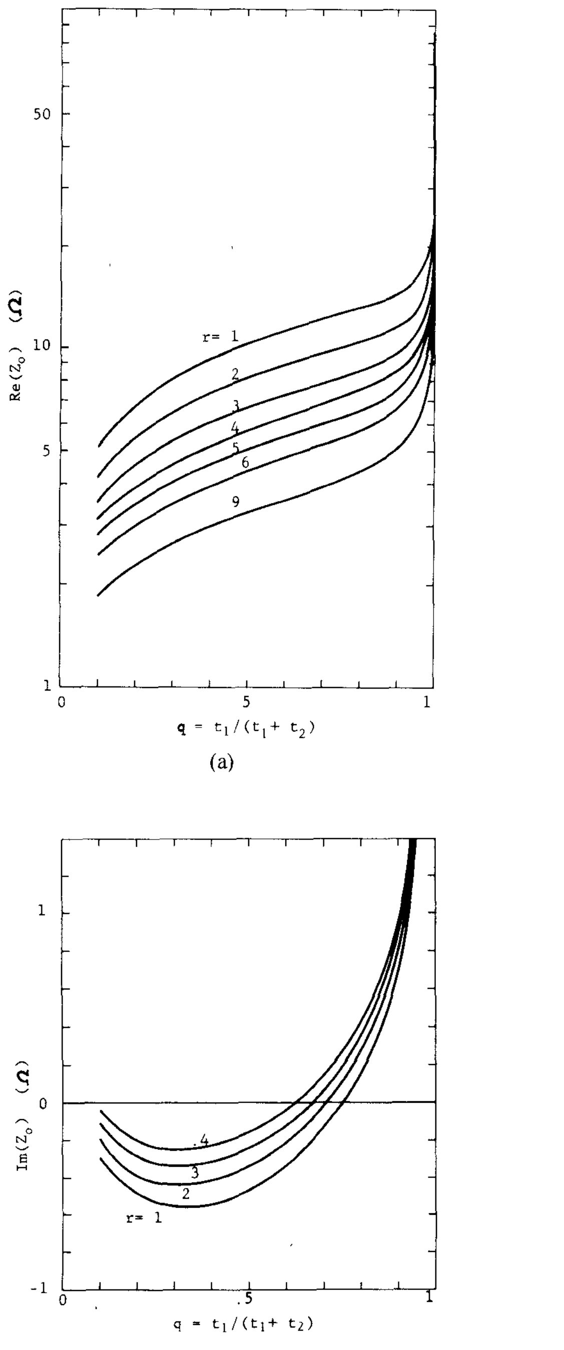

Fig. 6. (a) Real part of the characteristic impedance of the MISCPW of Fig. 4. (b) Imaginary part of the characteristic impedance of the MISCPW of Fig. 4.

is convenient to use narrow strip conductors and proper ratios between insulating and semiconducting layer thicknesses. In practical cases, however, the attenuation cannot be reduced indefinitely by reducing the strip width, since this will also have the effect of increasing the conductor loss. For a given geometry of the metallization, highest Q values are obtained for q ranging from 0.6 (for $r > 0.2$) to 0.7 (for $r < 0.2$). An investigation of the α behavior versus ρ for $q = 0.7$, $r = 0.1$ has shown that the optimum resistivity for minimum attenuation is about the same as the previous one.

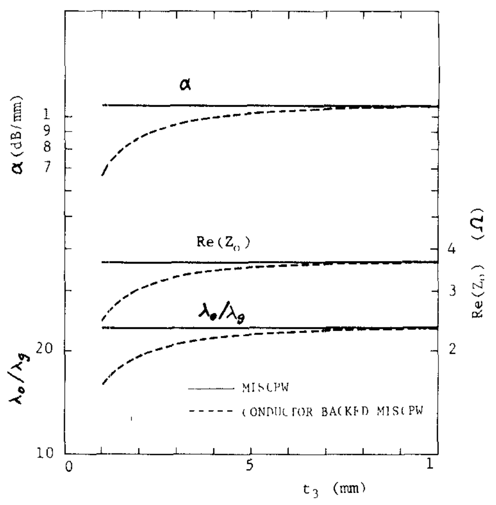

Fig. 7. Slow-wave factor, attenuation, and characteristic impedance as functions of the semi-insulating layer thickness of MISCPW.

The behavior of the complex characteristic impedance as a function of q and r is shown in Fig. 6(a) and (b). The behavior of the real part can be understood from a qualitative point of view in terms of the characteristic impedance of a quasi-TEM transmission line. The presence of the semiconducting layer has the effect of confining the electric field to the insulating layer, thus increasing the capacitance per unit length of the line and decreasing the characteristic impedance. Fig. 6(b) shows that the characteristic impedance has a generally small imaginary part of inductive or capacitive type depending on the geometry of the structure. As the semiconducting layer becomes very thin ($q \sim 1$), both the real and imaginary part of Z_0 undergo a very sharp increase. In the limit for $q = 1$, i.e., when the semiconducting layer is absent, the real part assumes much higher values, while the imaginary part becomes zero (not shown in Fig. (6b)).

B. Effect of Semiinsulating Layer Thickness

The effect of the semi-insulating layer thickness t_3 is illustrated ($q = 0.8$, $r = 0.5$) in Fig. 7 for a MISCPW with and without a ground plane on the back of the substrate. As t_3 decreases from 1.0 to 0.1 mm, the characteristics of the standard MISCPW remain practically unchanged. In the presence of a back conducting plane, on the contrary, the characteristics of the MISCPW are modified for t_3 smaller than 0.5 mm. The increased capacitance per unit length, due to the additional metallic plane, is responsible for the lower characteristic impedance. This figure indicates that the adoption of a back ground plane could be advantageous in reducing attenuation.

C. Effect of Distance Between Ground Planes

It has been already noted (see Fig. 4) that the attenuation can be reduced, for a fixed distance $s + 2w$ between the ground planes, by reducing the strip width s. Even lower attenuations can be obtained by a simultaneous reduction of $s + 2w$ and s. Fig. 8 shows the computed characteristics versus $s + 2w$ of a MISCPW with $q = 0.5$,

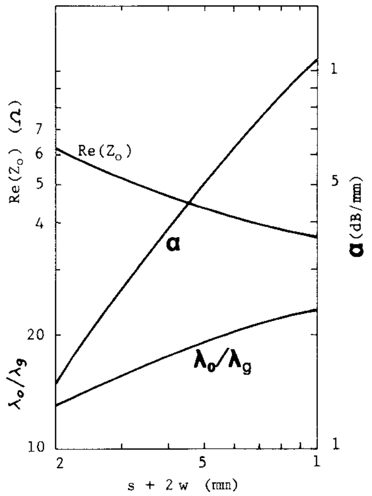

Fig. 8. Slow-wave factor, attenuation, and characteristic impedance as functions of the distance between ground planes.

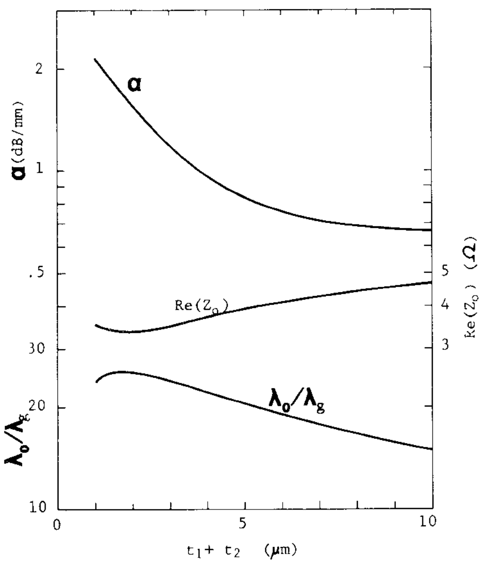

Fig 9. Slow-wave factor, attenuation, and characteristic impedance as functions of the overall thickness of the insulating and semiconducting layers.

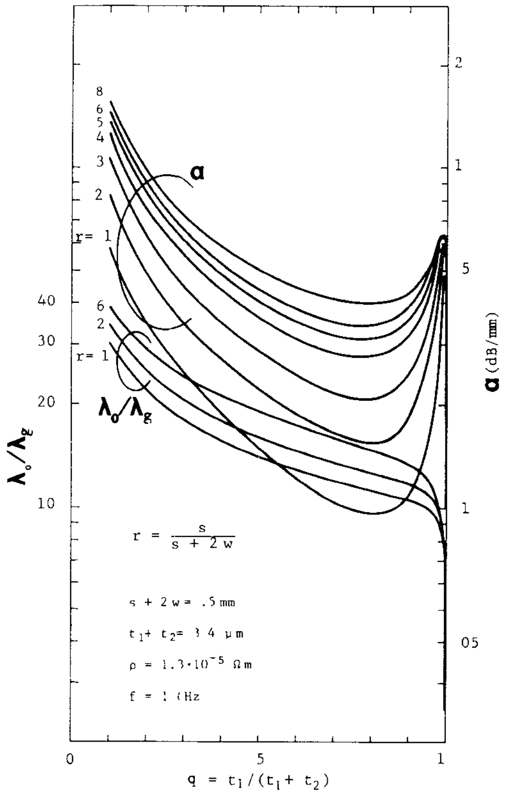

Fig. 10. Same as Fig. 4, except for with $s+2w=0.5$ mm and $t_3=0.2$ mm.

$r=0.8$. (Since r is kept constant, s varies from 0.8 to 0.16 mm as $w+2s$ varies from 1.0 to 0.2 mm.) It is seen that the attenuation of the structure can be reduced by about one order of magnitude by reducing the dimensions of the printed circuit; this has also the effect of increasing the Q of the line, since the slow-wave factor undergoes a much smaller reduction. A similar but not so marked effect is obtained by increasing the overall thickness of the insulating and semiconducting layers, as shown in Fig. 9. This way of reducing the attenuation, however, may be impractical because of technological problems.

We have then computed the characteristics of MISCPW having a distance between ground planes reduced with respect to the case of Fig. 4. As shown in Fig. 10, the general behaviors of α and λ_0/λ_g are about the same as the previous ones, but the attenuation is considerably reduced and attains a value lower than 0.1 dB/mm for $q=0.8$, $r=0.1$. The slowing factor is also reduced, but to a lesser extent, so that higher values (up to ~ 3.4) of Q are obtained. In any case, except for very small values of the semiconducting layer thickness ($q \sim 1$), slowings better than 10 are obtained. Fig. 11 shows the computed behavior of the real part of the characteristic impedance, which is slightly higher than in the previous case.

D. Comparison between Different Structures

Finally, Fig. 12 shows a comparison between the frequency behaviors of various structures. The a curves represent the computed values of attenuation and slow-wave factor of the original structure tested by Hasegawa: α varies from 2 dB/mm at $f=1$ GHz up to more than 20 dB/mm at $f=10$ GHz, while λ_0/λ_g varies from 30 to 11 correspondingly. The b curves represent the computed characteristics of one of the structures of Fig. 10, with $r=0.1$, $q=0.8$. In this case, the attenuation is reduced by one order of magnitude, while the slowing factor is about 10 in the whole frequency range. Even lower attenuations can be obtained, as shown by the third structure (c curves) having $s+2w=0.25$ mm. The slowing factor, though lower than in the other case, may be still considered as satisfactory. It is interesting to compare these results with those relative to the cross-tie CPW, which has been proposed by Seky and Hasegawa [11] as an alternative to the MISCPW. The Q values of the four structures of Fig. 12 are, at $f=1$ GHz, 0.46 for a, 3.37 for b, 7.1 for c, 1.4 (CT-CPW). Although conductor loss has not been included in the analysis, these results suggest that the MISCPW is capable of supporting slow-wave propagation with comparable or even better attenuation characteristics with respect to the

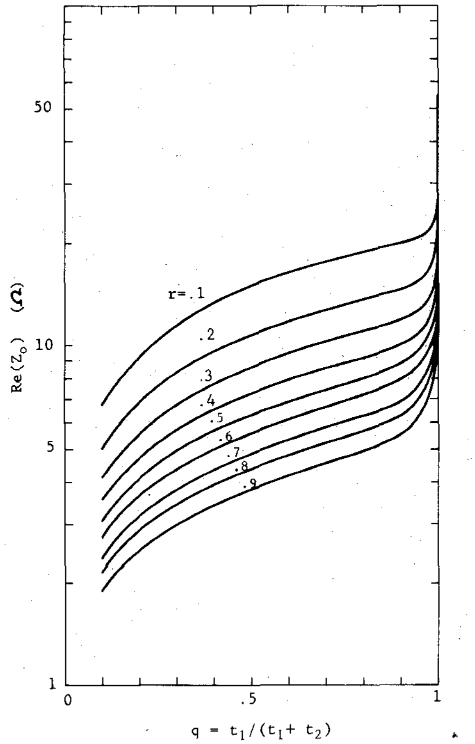

Fig. 11. Same as Fig. 6(a), except for with $s+2w=0.5$ mm and $t_3=0.2$ mm.

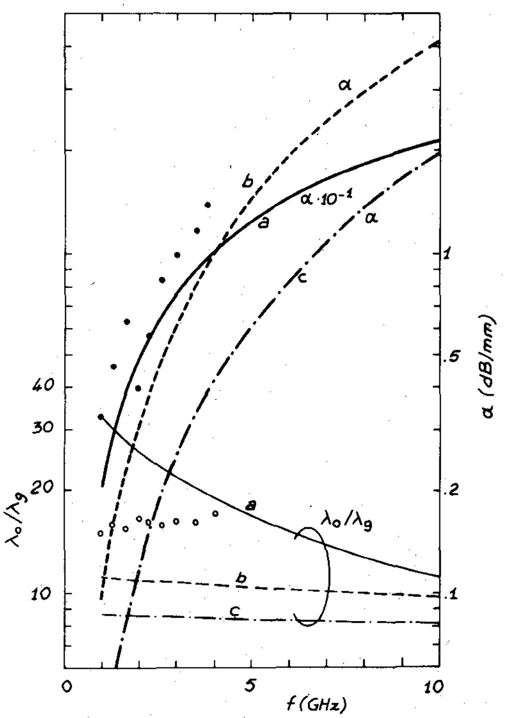

Fig. 12. Comparison between the frequency behaviors of different MISCPW. Dots represent experimental values for CT CPW [11].

cross-tie CPW, provided a suitable optimization of its parameters is made.

IV. Conclusions

A full-wave mode-matching technique has been used for computing the characteristics (slow-wave factor, attenuation, characteristic impedance) of MISCPW in terms of various geometrical parameters and frequency. Theoretical results indicate that low-loss propagation with useful slow-wave factors can be obtained adopting proper shape factors and doping levels of the semiconducting layer. Attenuations lower than 0.1 dB/mm with slowing factors of about 10 at $f=1$ GHz are theoretically predicted. These results render the MISCPW competitive with respect to alternative configurations [11] proposed for applications in the area of MMIC.

References

[1] R. A. Pucel, "Design considerations for monolithic microwave circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 513–534, 1981.
[2] W. Heinrich and H. L. Hartnagel, "Wave-theoretical analysis of signal propagation on FET electrodes," *Electron. Lett.*, pp. 65–67, Jan. 1983.
[3] P. Kennis and L. Faucon, "Rigourous analysis of planar M.I.S. transmission lines," *Electron. Lett.*, vol. 17, no. 13, pp. 454–456, 1981.
[4] H. Hasegawa, M. Furukawa, and H. Yanai, "Properties of microstrip line on Si–SiO$_2$ system," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 869–881, 1971.
[5] D. Jager and W. Rabus, "Bias dependent phase delay of Schottky contact microstrip lines," *Electron. Lett.*, vol. 9, no. 9, pp. 201–203, 1973.
[6] H. Hasegawa and H. Okizaki, "M.I.S. and Schottky slow-wave coplanar stripline on GaAs substrates," *Electron. Lett.*, vol. 13, no. 22, pp. 663–664, 1977.
[7] G. W. Hughes and R. M. White, "Microwave properties of nonlinear MIS and Schottky-barrier microstrip," *IEEE Trans. Electron Devices*, vol. ED-22, pp. 945–956, 1975.
[8] Y. C. Shih and T. Itoh, "Analysis of printed transmission lines for monolithic integrated circuits," *Electron. Lett.*, vol. 18, no. 14, pp. 585–586, July 1982.
[9] Y. Fukuoka and T. Itoh, "Analysis of slow-wave phenomena in coplanar waveguide on a semiconductor substrate," *Electron. Lett.*, vol. 18, no. 14, pp. 589–590, July 1982.
[10] R. Sorrentino and G. Leuzzi, "Full-wave analysis of integrated transmission lines on layered lossy media," *Electron. Lett.*, vol. 18, no. 14, pp. 607–609, July 1982.
[11] S. Seki and H. Hasegawa, "Cross-tie slow-wave coplanar waveguide on semi-insulating GaAs substrate," *Electron. Lett.*, vol. 17, pp. 940–941, 1981.
[12] Y. C. Shih and T. Itoh, "Analysis of conductor backed coplanar waveguide," *Electron. Lett.*, vol. 18, pp. 538–540, June 1982.
[13] P. Lampariello and R. Sorrentino, "The ZEPLS program for solving characteristic equations of electromagnetic structures," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 457–458, May 1975. See also W. Zieniutycz, "Comments on the ZEPLS program," and Authors' Reply, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, p. 420, May 1983.

Roberto Sorrentino (M'77) received the degree in electronic engineering from the University of Rome La Sapienza, Rome, Italy, in 1971.

He then joined the Institute of Electronics of the same University under a fellowship of the Italian Ministry of Education. Since 1974, he has been an Assistant Professor at the Rome University La Sapienza. He was also "professore incaricato" of Microwaves at the University of Catania, Catania, Italy, from 1975 to 1976, and of the University of Ancona, Ancona, Italy, from

1976 to 1977. From 1977 to 1981, he was professore incaricato of Solid State Electronics at the University of Rome La Sapienza, where he is presently an Associate Professor of Microwave Measurements. From September to December 1983, he was appointed as a Research Fellow in the Electrical Engineering Department of the University of Texas at Austin, Austin, TX.

His research activities have been concerned with electromagnetic wave propagation in anisotropic media, numerical solution of electromagnetic structures, electromagnetic field interaction with biological tissues, and mainly with the analysis and design of microwave and millimeter-wave integrated circuits.

Since 1978, Dr. Sorrentino has been a member of the Executive Committee of the IEEE Middle and South Italy Section. He is also a member of the Italian Electrical Society (AEI).

Giorgio Leuzzi was born in Rome, Italy, on November 18, 1957. He received the degree in electronic engineering from the University of Rome in July 1982. In 1984, at the end of his military service, he will join the Department of Electronics of the II University of Rome, Tor Vergata, as a Research Associate of Applied Electronics.

Agnès Silbermann was born in Paris, France, on April 26, 1958. She received the degree in electronic engineering from the University of Rome, Rome, Italy, in December 1981. She then joined the Department of Electronics of the University of Rome, La Sapienza. Since November 1982, she has also been with Elettronica S.P.A., Rome, where she is involved in the design of wide-band microwave circuits.

An Efficient 200–290-GHz Frequency Tripler Incorporating A Novel Stripline Structure

JOHN W. ARCHER, SENIOR MEMBER, IEEE

Abstract —**This paper describes a broadly tuneable frequency tripler which can provide more than 2-mW output power at any frequency between 200 and 290 GHz. It is derived from an earlier narrow-band prototype design, with the major improvements being the use of a new low-pass filter design implemented using a novel suspended substrate stripline structure, an optimized waveguide transformer, and a lower loss contacting output backshort.**

I. Introduction

IN RECENT YEARS, varactor frequency multipliers have become a practical source of local oscillator signals in millimeter wavelength heterodyne receivers [1], [2]. The achievement of optimum performance in a recently constructed multiple-mixer, cryogenic receiver for the 200–350-GHz band [3] necessitated the development of a single frequency tripler which could provide significant output power in the 200–290-GHz frequency range. This paper describes the device developed to meet this requirement. The design of the frequency multiplier was based on an earlier prototype structure [1] which exhibited a significantly narrower operating bandwidth. An improved stripline low-pass filter, an optimized waveguide transformer, and a lower loss contacting backshort represent the major changes made to the original harmonic generator design to enable it to meet the new performance specifications. The resulting device provides a significantly improved output power bandwidth product when compared with previous designs [2], [4].

Manuscript received July 29, 1983; revised November 21, 1983.

The author is with the National Radio Astronomy Observatory, Charlottesville, VA 22903. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

II. General Mount Description

The harmonic generator employs a split block construction which has been successfully used in a number of different multiplier designs [5]. The geometry used in this frequency tripler is shown in Fig. 1. Power incident in the full height input waveguide is fed to the varactor diode via a tuneable transition and a seven-section suspended substrate low-pass filter, which passes the pump frequency with low loss, but is cut off for higher harmonics. The

0018-9480/84/0400-0416$01.00 ©1984 IEEE