IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES VOL. MTT-13, NO. 6 NOVEMBER, 1965

A Ferroelectric Microwave Switch

J. W. AMOSS, M. R. DONALDSON, SENIOR MEMBER, IEEE, L. J. LAVEDAN, MEMBER, IEEE,
A. L. STANFORD, AND J. E. PIPPIN, SENIOR MEMBER, IEEE

Abstract—**The rapid variation of an admittance shunting a transmission line is a well-known technique for switching microwave power. The application of a switching voltage to a ferroelectric material provides a convenient means for rapidly varying an admittance between significantly different states. A multistub transmission-reflection-type switch actuated by a switching voltage of 1000 volts has been studied. The operation of the switch depends upon the ability of a ferroelectric variable capacitor to change its capacitance upon application of a switching voltage. A change in capacitance represented by a ratio of two to one results in substantial change in the input admittance of the prototype network shunting the transmission line.**

The prototype network is a shunt stub and is spaced nominally at $\lambda/4$ intervals along the transmission line to form a multistub switch. Each shunt stub includes a ferroelectric variable capacitance which employs lead strontium titanate ($Pb_{0.315}Sr_{0.685}TiO_3$) as the ferroelectric material.

Both theoretical and experimental curves of isolation and insertion loss vs. frequency are given for two- and three-stub versions of the switch.

For switching voltages of the order of 1000 volts, ferroelectric switches with an isolation of 40 dB, an insertion loss less than 1.0 dB, and a bandwidth of 10 percent are feasible.

INTRODUCTION

THE VARIATION of an admittance shunting a transmission line is a well-known technique for switching microwave power.[1–5] Specifically, the application of a switching voltage to a capacitor made of ferroelectric material provides a convenient means for the rapid variation of an admittance between significantly different states. Multistub switches using ferroelectric capacitors have been studied at lower microwave frequencies. The operation of the switches depends upon the change in capacitance of a ferroelectric capacitor upon the application of a switching voltage. A change in capacitance represented by a ratio of two to one results in a substantial change in the input admittance of the prototype network shunting the transmission line.

SINGLE STUB SWITCH

The prototype switching network, shown schematically in Fig. 1, consists of an inductive line, the ferroelectric variable capacitor, a quarter wavelength stub line, and an input tuning capacitor. The ferroelectric capacitor can be switched from a high capacitance value (state B) to a low capacitance value (state A) upon the application of a dc biasing voltage. The factor P represents the fractional change in capacitance between states B and A. The inductive line is adjusted to resonate the ferroelectric capacitor at the midband frequency with the switch in state A. This minimizes the admittance of the ferroelectric capacitor-inductive stub combination at the plane of the ferroelectric capacitor. When transformed through the quarter wavelength of stub line, this results in a high admittance across the main line. Thus, for this state maximum power is reflected.

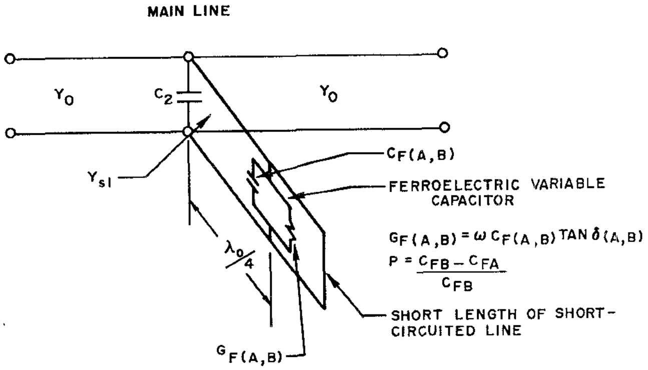

Fig. 1. Schematic of single-stub prototype switch.

Removing the bias voltage, which increases the value of the ferroelectric capacitor, causes the susceptance of the ferroelectric capacitor-inductive line combination to be capacitive. This capacitive susceptance, transformed through the quarter wavelength line, appears inductive and in parallel with the capacitor C_2. The value of C_2 is adjusted to resonate with the inductive susceptance presented by the stub in state B. This causes a minimum admittance to appear across the main line, resulting in maximum power transmission.

Manuscript received May 7, 1965; revised July 16, 1965. This work was performed by the Sperry Microwave Electronics Co. under Contract DA 36-039-AMC-02340(E) and sponsored by the Microwave and Inductive Devices Branch, U. S. Army Electronics Labs., Fort Monmouth, N. J.

J. W. Amoss and L. J. Lavedan are with the Research Section, Sperry Microwave Electronics Co., Clearwater, Fla.
M. R. Donaldson is with the College of Engineering, University of South Florida, Tampa, Fla.
A. L. Stanford is with the School of Physics, Georgia Institute of Technology, Atlanta, Ga.
J. E. Pippin is with Scientific-Atlanta, Inc., Atlanta, Ga.

[1] R. V. Garver, "Theory of TEM diode switching," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-9, pp. 224–238, May 1961.

[2] R. V. Garver and J. A. Rosado, "Broad-band TEM diode limiting," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 302–310, September 1962.

[3] J. C. Hoover, "A 6-kw peak power varactor duplexer," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 476–479, November 1962.

[4] M. E. Hines, "Fundamental limitations in RF switching and phase shifting using semiconductor diodes," *Proc. IEEE*, vol. 52, pp. 697–708, June 1964.

[5] R. V. Garver, Fundamental limitations in RF switching using semiconductor diodes, *Proc. IEEE*, vol. 52, pp. 1382–1384, November 1964.

It can be shown that midband isolation and insertion loss for a single stub switch are given approximately by the following equations:

$$L_{1A}(\omega_0) = \text{isolation in dB at midband,}$$

$$= 20 \log_{10} \left| 1 + \frac{(Y_{s1})^2}{2 Y_0 \omega_0 C_{FA} \tan \delta_A} \right| \tag{1a}$$

$$L_{1B}(\omega_0) = \text{insertion loss in dB at midband}$$

$$= 20 \log_{10} \left| 1 + \frac{(Y_{s1})^2 \tan \delta_B}{2 Y_0 \omega_0 C_{FA}} \, \frac{1 - P}{P^2} \right| \tag{1b}$$

where

ω_0 = midband angular frequency,
C_{FA}, C_{FB} = ferroelectric variable capacitance, state A and state B, respectively,
$\tan \delta_A$, $\tan \delta_B$ = loss tangent of ferroelectric capacitor, state A and state B, respectively,
Y_0, Y_{s1} = characteristic admittance of the main transmission line and the stub line, respectively,
P = fractional change in ferroelectric capacitance, and
$P = (C_{FA} - C_{FB})/C_{FB}$.

These equations show that both the midband isolation and the midband insertion loss increase with Y_{s1} and decrease with Y_0, ω_0, and C_{FA}.

Equation (1a) shows that the isolation increases with a decrease in $\tan \delta_A$, while (1b) shows that the insertion loss decreases with a decrease in $\tan \delta_B$ and an increase in P. Thus, for high switching ratios the ferroelectric material utilized in the switching capacitor should have a small average loss tangent and a large fractional change in capacitance. Substituting typical values in (1a) and (1b) yields about 20 dB isolation with about 0.5 dB insertion loss at midband.

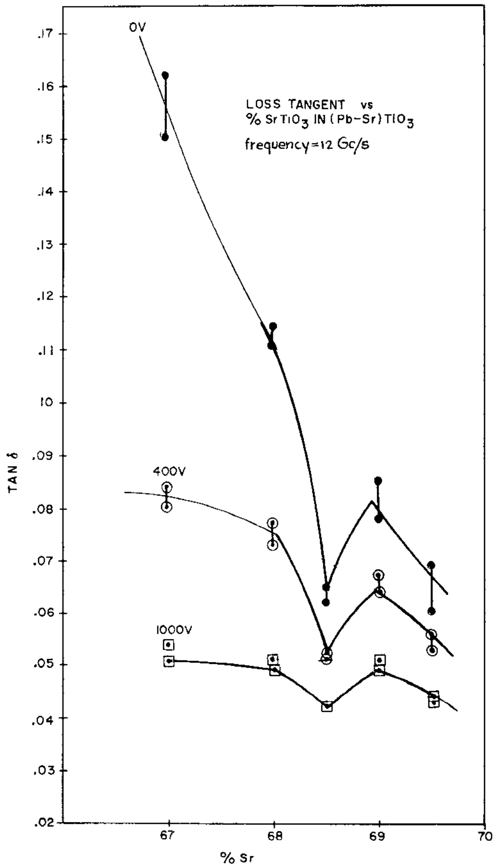

Fig. 2. Loss tangent as a function of strontium content at three bias voltage values.

Ferroelectric Materials and Encapsulation

The more common ferroelectric materials and their general properties have received considerable interest in the past decade. One characteristic of these materials is that their relative susceptibility obeys the Curie-Weiss law.

In the region below its characteristic Curie temperature, the material exhibits spontaneous polarization, dielectric hysteresis, a relatively high permittivity, both piezoelectric and pyroelectric properties,[6] and a nonlinear dependence of its permittivity on applied electric field strength. Above the Curie temperature, the material is better behaved and, in general, has a lower loss tangent but continues to exhibit nonlinear response to electric fields. It is the nonlinear dependence of the permittivity on an applied dc electric field that provides the basis for switching action. To eliminate hysteresis, piezoelectric, pyroelectric, and other undesired effects which are exhibited below the Curie temperature, the materials used were those having a Curie temperature below the operating temperature. The nonlinearity of most materials is also greatest in this region.

The results of loss-tangent measurements on a series of lead strontium titanate materials appear in Fig. 2. Voltage applied to the material is a parameter of the curves. A rather sharp decrease in tan δ is noted in the unbiased material as 70 percent SrTiO$_3$ is approached. An apparent anomaly, which has not been explained, appears at 68.5 percent. It may be due to some fortunate factor which affected the material preparation.

Table I shows the results of percent capacitance change at 1 Mc/s with application of 400 and 1000 volts on capacitors made of lead strontium titanate material. The nonlinearity decreases with increasing strontium titanate content in a rather smooth manner, and since PS-68.5[7] had a significantly lower loss, this material was chosen as the most suitable of the series.

It was deemed advantageous from measurement, device design, and material evaluation considerations, to

---

[6] Spontaneous polarization and dielectric hysteresis are analogous to spontaneous magnetization and magnetic hysteresis found in certain magnetic materials. Piezoelectric effect is the phenomenon of a mechanical stress producing an electric polarization. Pyroelectric effect is the phenomenon of a change in temperature producing a change in electric polarization.

[7] This notation refers to Pb$_{31.5}$SR$_{68.5}$TiO$_3$, the number 68.5 denoting the percent strontium titanate in the mixed composition, and the letters P and S referring to lead and strontium, respectively.

TABLE I

Percent Change in Capacitance of (Pb-Sr)TiO_3 Ceramics with 400 and 1000 Volts Applied. All Samples were 20-Mils Thick.

	$C_F/C_F \times 100$ Percent at 400 volts	$C_F/C_F \times 100$ Percent at 1000 volts
PS-67	55	79
PS-68	42	68
PS-68.5	33	62
PS-69	26	55
PS-69.5	26	57

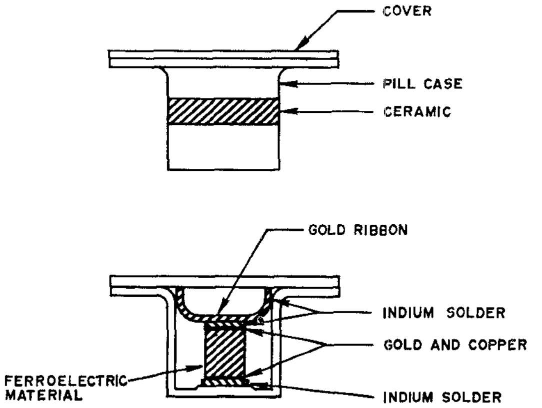

Fig. 3. Typical encapsulation of ferroelectric material.

encapsulate the material into a package forming a separate element rather than to incorporate the material directly into the switch itself. A typical encapsulation of ferroelectric material is shown in Fig. 3. The element resulting from the encapsulation of ferroelectric material into a package suitable for use at microwave frequencies has been termed a FEVAC, a word formed from the initial letters of FErroelectric VAriable Capacitor. The package is a commercially available pill type used extensively in the manufacture of varactor and tunnel diodes and is particularly suited for strip-line circuits. A ceramic mixture of 31.5 percent lead titanate and 68.5 percent strontium titanate was found to be the best of the materials tested for switching purposes. FEVACs were made with this material which yielded fractional capacitance changes of 0.60 and average loss tangents of about 0.06 at 1.2 Gc/s.

Other materials prepared and tested for switching applications were various ceramic compositions of barium strontium titanate, lead strontium titanate, lead calcium titanate, lead strontium nickel titanate, and lead strontium erbium titanate.

Multistub Switch

Since the operation of the prototype switch depends upon different resonance conditions appearing across the main line, it is inherently a narrow-band device. To increase the bandwidth and isolation, cascading of single stub switches was studied. The prototype single stub switch discussed previously was used in deriving the multistub switch. The switch configuration shown in Fig. 4 employs n prototype shunt stubs. Each of the n stubs, Y_1, Y_2, $Y_3 \cdots Y_n$, contains a FEVAC and switching is obtained as in the prototype stub; that is, by biasing the FEVACs between two values, state A and state B. The n stubs are separated by $(n-1)$ sections of transmission line.

It can be shown that the loss incurred by inserting the switch into a matched network is

$$L_{n(A,B)} = 20 \log \left| \frac{C_{n(A,B)}}{2Y_0} \right| \text{(dB)},$$

where $C_{n(A,B)}$ is the C element (for the two states A and B) in the $ABCD$ matrix for the overall network of Fig. 4 including the source and load, and Y_0 is the characteristic admittance of the main transmission line. A digital computer was used to study the effect on isolation and insertion loss when certain parameters were changed. This was done for one-, two-, three-, four-, and five-stub switches. The parameters which were changed were

$\tan \delta$ = loss tangent of material
P = fractional change in FEVAC capacitance
Y_{sn} = admittance of stub line
Y_{0n} = admittance of main line between stubs
βl_{sn} = length of line between main line and FEVAC
βl_n = length of line between stubs
ω_{0n} = resonant frequency of FEVAC-inductive stub combination.

The computer results indicated that a three-stub switch could be built to give greater than 40 dB isolation with about 1-dB insertion loss over a 10 percent bandwidth. Using the computer results as a guide, two- and three-stub switches were designed and built to operate at a center frequency of 1.2 Gc/s.

The final configuration of the three-stub switch is shown in Fig. 5. The switch is of strip-line construction utilizing type N connectors. Copper clad laminated glass is used as the center conductor. The dielectric ground plane spacing is approximately 125 mils, which is quite adequate for the pill-type package of 58 mils. The characteristic impedance of the main line is 50 ohms. The distance between stubs and between FEVAC and main center conductor is adjusted to a nominal quarter wavelength at midband frequency. The length of the tuning elements is adjusted for each stub to assure optimum insertion loss and isolation over the operating frequency band.

FEVAC bias voltage is applied by making contact to the FEVAC directly. The dc return is made through the center conductor which is grounded by the shorting plate. A feed-through capacitor is used at the ground plane to provide RF bypass. External to the microwave device, individual bias adjustment potentiometers are provided to permit fine tuning of the resonant frequencies after the inductive lines behind the FEVACs are coarse-adjusted.

The entire device has been placed in an aluminum

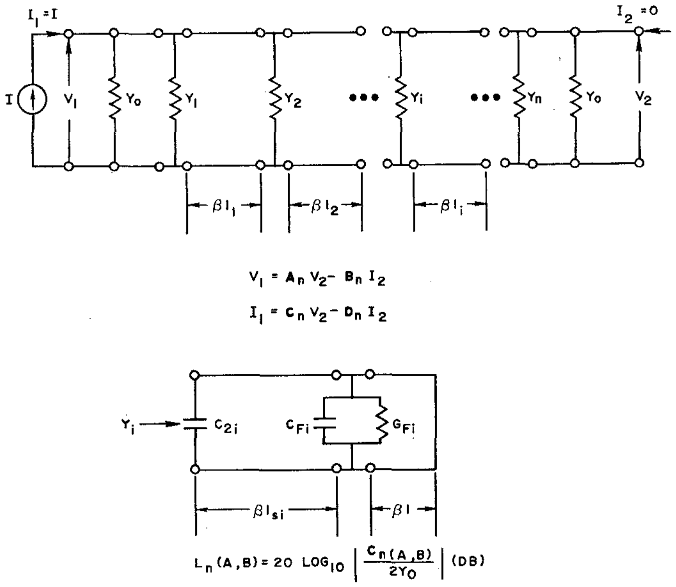

Fig. 4. Multistub ferroelectric switch configuration.

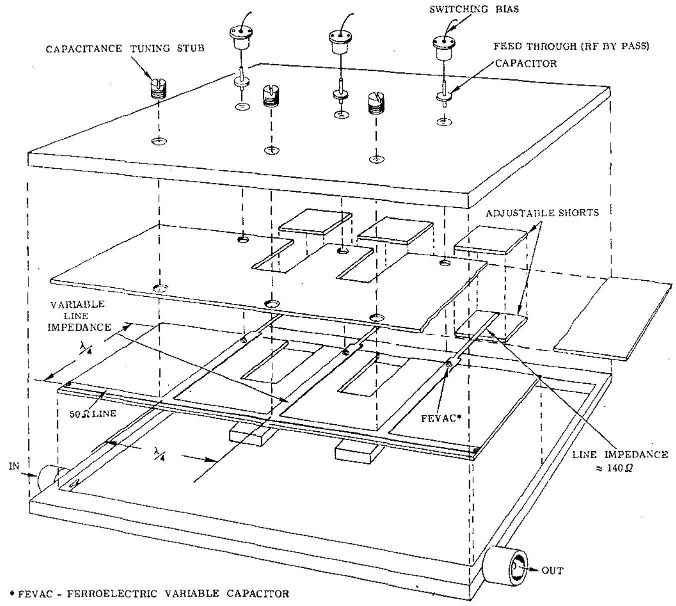

Fig. 5. Sketch of a three-stub ferroelectric switch.

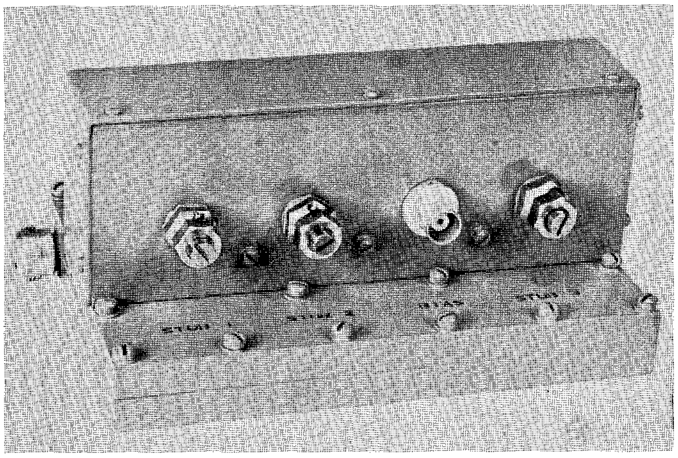

Fig. 6. Photograph of L-band ferroelectric switch.

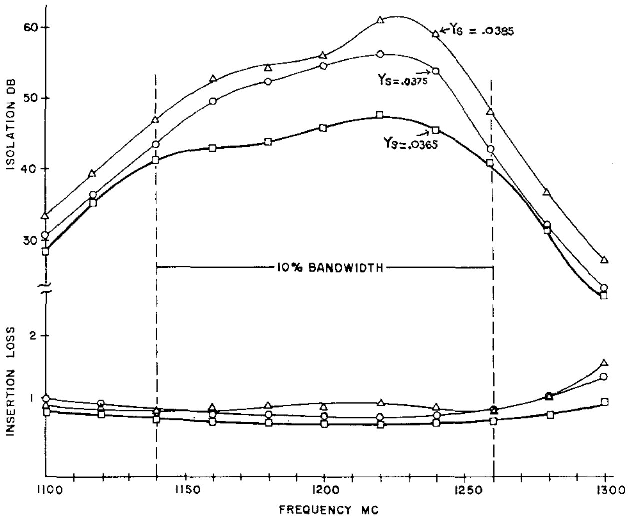

Fig. 7. Experimental data for a three-stub switch. Set of curves are for different values of stub admittance.

shell to prevent RF leakage as well as to protect the user against accidental dc shock from the high-voltage bias circuit. The completed switch is shown in Fig. 6. The box-like enclosure mounted on the switch contains the individual bias adjustment potentiometers. Experimental plots of isolation and insertion loss as a function of frequency for the final three-stub switch are shown in Fig. 7. These sets of curves show the effect of varying the admittance of the lines between the FEVACs and the main line. As the admittance of this length of line is decreased, both the isolation and the insertion loss decrease. Notice that the isolation is greater than 40 dB and the insertion loss is less than 1 dB over a 10 percent bandwidth for the set of curves indicated by the heavy line. Within the authors' knowledge, these are the best results obtained to date from a switch using ferroelectric material.

SWITCHING TIME

For rapid switching, it was necessary to remove the fine tuning potentiometers associated with the dc biasing circuit. Pulses whose amplitude varied from 0–1000 volts dc with pulse widths of approximately 2 μs and rise time of approximately 0.5 μs were used to switch the unit from the transmit condition to the reflect condition. Figure 8 is an oscilloscope photograph of the dc switching pulse superimposed upon the RF output pulse. The gain of the channel displaying the dc switching pulse was adjusted to make full scale represent 1000 volts. It can be seen that at approximately 750 volts the switch had reached the maximum isolation condition.

Similar tests were performed with a voltage excursion of approximately 50 volts about a 500-volt bias point. The shape of the RF output curve followed the pulse curve to the minimum limit of the pulse generator (that is, 250-ns pulse time and 100-ns rise time).

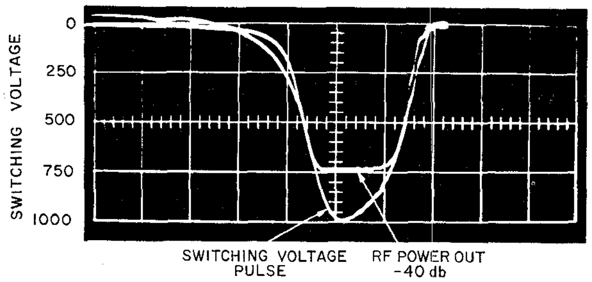

Fig. 8. Oscilloscope photograph of dc switching pulse and RF output pulse.

From these tests, it is reasonable to say that the switching time is less than 100 ns.

Power Handling Capability

Average and peak power levels at various pulse widths were used to check the power handling capability of the ferroelectric switch.

It was found that the maximum average power the switch could handle and still exhibit the above quoted characteristics was approximately 500 milliwatts. This value changes slightly with peak power and pulse width. At an average power level of 500 mW the unit starts to limit and reflection occurs. No apparent damage occurred up to a maximum input power of 5 watts.

It appears feasible that the unit could be retuned to operate at higher power levels but then it would not function at reduced powers.

Acknowledgment

The authors gratefully acknowledge the assistance of John Agrios and the Computer Laboratory personnel at USAEL in providing the numerical data related to the computer program portion of this study. The authors also wish to acknowledge the assistance of Karl Schmidt who prepared many of the curves from the computer data, and Roger Denhard for assistance in carrying out the measurements.

Bibliography

[1] W. J. Gemulla and R. D. Hall, "Ferroelectrics at microwave frequencies," *Microwave J.*, vol. 3, pp. 47–51, February 1960.
[2] C. P. Sharpe and C. G. Brochus, "Investigation of microwave properties of ferroelectric materials (final report)," University of Michigan Research Inst., Ann Arbor, Michigan, Rept. 2732-4-F, March 1959.
[3] M. Cohn and A. F. Eikenburg, "Ferroelectric phase shifters for VHF and UHF," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 536–548, November 1962.
[4] G. Ruprecht, B. D. Silverman, and R. J. Bell, "Investigation of the microwave properties of ferroelectrics," AFCRC Labs., Bedford, Mass., Rept. AF 19(604)-4085, June 16, 1958, October 15, 1960.

Computation of Impedance and Attenuation of TEM-Lines by Finite Difference Methods

M. V. SCHNEIDER, MEMBER, IEEE

Abstract—The characteristic impedance and the attenuation of transmission lines supporting TEM modes can be computed by using finite difference methods for solving the Laplace equation for the domain defined by the inner and the outer conductor. The difference equations can be solved by machine computation and the impedance and the attenuation is obtained by integrating the field gradients and the squares of field gradients over both boundaries.

The case of a shielded strip transmission line is treated as a numerical example. A computation time of approximately 0.015 hour on the IBM 7094 is required for achieving an accuracy of 0.5 percent for the impedance and 2 percent for the attenuation.

The finite difference method is also used for lines which are partially filled with dielectric material and it is concluded that low attenuations are obtained by placing the dielectric material in such a way that high field regions are avoided.

Manuscript received May 14, 1965; revised August 9, 1965.
The author is with Bell Telephone Laboratories, Inc., Holmdel, N. J.

Introduction

THE COMPUTATION of the characteristic impedance and the attenuation of various transmission lines supporting TEM modes is a problem of considerable importance for the design of microwave circuits. The impedance and the attenuation of such lines can be computed by using conformal transformation techniques. Various dictionaries and lists of conformal transformations covering a large number of cases have been published by Moon and Spencer [1], Kober [2], and Binns and Lawrenson [3], however, only a limited number of the transformations are applicable to transmission lines which occur in practice. It is, therefore, understandable that considerable work has been spent on numerical techniques for computing the characteristic impedance of several transmission lines.