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Propagation Characteristics of Some Novel Coplanar Waveguide Transmission Lines on GaAs at MM-Wave Frequencies

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PROPAGATION CHARACTERISTICS OF SOME NOVEL COPLANAR WAVEGUIDE TRANSMISSION LINES ON GaAs AT MM-WAVE FREQUENCIES

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E-3335

SUMMARY

Three new Coplanar Waveguide (CPW) transmission lines, namely, Suspended CPW (SCPW), Stripline-like Suspended CPW (SSCPW) and Inverted CPW (ICPW), are proposed and also analyzed for their propagation characteristics for the very first time. The substrate thickness, permittivity and dimensions of housing are assumed to be arbitrary.

These structures have the following advantages over conventional CPW. Firstly, the ratio of guide wavelength to free space wavelength is closer to unity which results in larger dimensions and hence lower tolerances. Secondly, the effective dielectric constant is lower and hence the electromagnetic field energies are concentrated more in the air regions which should lower the attenuation. Thirdly, for a prescribed impedance level, the above structures have a wider slot width for identical strip width. Thus low impedance lines can be achieved with reasonable slot dimensions. Fourthly, in an inverted CPW shunt mounting of active devices, such as Gunn and IMPATT diodes, between the strip and the metal trough is possible. This feature further enhances the attractiveness of the above structures. Lastly, an E-plane probe type transition from a rectangular waveguide to suspended CPW can also be easily realized.

The computed results for GaAs at Ka-band illustrate the variation of normalized guide wavelength, effective dielectric constant and the characteristic impedance as a function of the (a) frequency; (b) distance of separation between the trough side walls; (c) normalized strip and slot widths; and lastly (d) normalized air gap.

I. INTRODUCTION

The conventional Coplanar Waveguide (CPW) on alumina substrate (ref. 1) is ideally suited for MIC Components, such as FET amplifiers (refs. 2 and 3) and balanced mixers (ref. 4). The Conductor Backed Coplanar Waveguide (CBCPW) on GaAs substrate (ref. 5) is suited for MMICs, where the additional ground plane not only acts as an efficient heat sink but also provides mechanical support to the thin and fragile substrate.

This paper presents three new Coplanar Waveguide structures, namely, Suspended Coplanar Waveguide (SCPW), Stripline-like Suspended Coplanar Waveguide (SSCPW), and Inverted Coplanar Waveguide (ICPW) and their computed propagation

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parameters, namely, the normalized guide wavelength λ'/λ, where λ is the free space wavelength, effective dielectric constant ε_{eff}, and characteristic impedance Z_0. The generic cross section of these structures are depicted in figure 1(a) to (e). These structures have the following advantages. Firstly, the ratio of guide wavelength to free space wavelength is closer to unity. Hence, circuit dimensions would be larger, which would ease fabrication tolerances at mm-wave frequencies. Secondly, the effective dielectric constant is lower and hence the electromagnetic field energies are concentrated more in the air regions which should lower attenuation. Thirdly, for a prescribed impedance level, the above structures have a wider slot width for identical strip width. Thus low impedance lines can be achieved with reasonable slot dimensions. Fourthly, in an ICPW shunt mounting of active devices, such as Gunn and IMPATT diodes, between the strip conductor and the metal trough is possible. Lastly, an E-plane probe-type transition from a rectangular waveguide to SCPW can also be easily realized.

The above structures are analyzed using Cohn's technique (ref. 6) which has been extended by the author to handle shielded slot-lines, coupled slot-lines, fin-lines, and CPW transmission lines (refs. 7 to 9). The assumptions made are (a) that the air gap below the substrate is of arbitrary height; (b) the dielectric substrate is isotropic, homogeneous; and of arbitrary thickness and relative permittivity, (c) the conducting ground plane and the zero thickness metalization on the substrate has infinite conductivity. An attractive feature of this analysis is that it is possible to model the conventional CPW or the CBCPW by allowing the airgap height to approach infinity or zero respectively, without causing numerical problems or increasing computing time.

II. ANALYSIS

A schematic diagram of the Coplanar Waveguide structures to be analyzed is shown in figure 1(a) to (e). These Coplanar Waveguide structures support the odd mode of an edge coupled slot line. The odd-mode electric and magnetic field components are illustrated in reference 10. From these illustrations it is clear that a magnetic wall can be placed at the plane of symmetry and the right half of the structure isolated. The equations for computing the propagation parameters are derived from those presented in reference 8. The total susceptance ηB_t at the plane of the slot for the SSCPW is

$$\eta B_t = \frac{1}{p}\left\{(\varepsilon_r + 1 - 2p^2)I + \sum_{n=0,1,2,\ldots}^{\infty}\left[v^2\left(1 - \frac{\coth\left(\frac{m\pi F_n H}{B}\right)}{F_n}\right) + M_n\right] \times \frac{\sin^2\left(\frac{m\pi\delta}{2}\right)}{m\left(\frac{m\pi\delta}{2}\right)^2}\sin^2\frac{m\pi\bar{\delta}}{2}\right\} \quad (1)$$

where

$$m = \frac{(2n + 1)}{2}$$

$$\eta = 376.7\ \Omega$$

$$\delta = \frac{W}{B}$$

$$\bar{\delta} = \frac{(S + W)}{B}$$

$$v = (p^2 - 1)^{1/2}$$

$$u = (\varepsilon_r - p^2)^{1/2}$$

$$F_n = \left[1 + \left(\frac{Bv}{anp}\right)^2\right]^{1/2}$$

$$F_{n1} = \left[1 - \left(\frac{Bu}{anp}\right)^2\right]^{1/2}$$

$$I = \frac{1}{(\pi\delta)^2} \cdot \left\{ - \frac{(\pi\bar{\delta})^2}{2} \ln \frac{\pi\bar{\delta}}{4} - \frac{(\pi\delta)^2}{2} \ln \frac{\pi\delta}{4} + \frac{[\pi(\bar{\delta} + \delta)]^2}{4} \ln \frac{\pi(\bar{\delta} + \delta)}{4} + \frac{[\pi(\bar{\delta} - \delta)]^2}{4} \ln \frac{\pi(\bar{\delta} - \delta)}{4} + \frac{(\pi\bar{\delta})^2\,(\pi\delta)^2}{96} \right\} \qquad (2)$$

For F_{n1} real, M_n is

$$M_n = \frac{\varepsilon_r \tanh r_{n1} - p^2 F_{n1}^2 \coth q_{n1}}{\left[1 + \left\{\frac{B}{a\left(\frac{2n + 1}{2}\right)}\right\}^2\right] F_{n1}} - u^2 \qquad (3)$$

where

$$r_{n1} = \frac{\left(\frac{2n + 1}{2}\right)\pi F_{n1} D}{B} + \tanh^{-1}\left\{\frac{F_{n1}}{\varepsilon_r F_n} \coth \frac{\left(\frac{2n + 1}{2}\right)\pi F_n (H - D)}{B}\right\} \qquad (4)$$

$$q_{n1} = \frac{\left(\frac{2n + 1}{2}\right)\pi F_{n1} D}{B} + \coth^{-1}\left\{\frac{F_n}{F_{n1}} \coth \frac{\left(\frac{2n + 1}{2}\right)\pi F_n (H - D)}{B}\right\} \qquad (5)$$

By replacing coth $(m\pi F_n H/B)$ by 1 in equation (1) the expression for ηB_t for the SCPW in obtained, and by replacing

$$\coth \frac{\left(\frac{2n+1}{2}\right)\pi F_n (H - D)}{B}$$ by 1 in equations (4) and (5) the expression for ηB_t for the ICPW in obtained. Finally, the expression for ηB_t for a conventional CPW is obtained by replacing coth $(m\pi F_n H/B)$ in equation (1) and also

$$\coth \frac{\left(\frac{2n+1}{2}\right)\pi F_n (H - D)}{B}$$ in equations (4) and (5) by 1.

In the case of a CBCPW, $\coth(m\pi F_n H/B)$ should be replaced by 1 and equation (3) gets modified to

$$M_n = \frac{\left(\varepsilon_r - p^2 F_{n1}^2\right) \coth q_{n1}}{\left[1 + \left\{\frac{B}{a\left(\frac{2n+1}{2}\right)}\right\}^2\right] F_{n1}} - u^2 \tag{6}$$

The equation for ηB_t is then solved using the procedure outlined in reference 6 to obtain λ'/λ, ε_{eff}, and Z_0.

III. NUMERICAL RESULTS AND DISCUSSIONS

A. Propagation Parameters

Conventional Coplanar Waveguide (CPW). - The computed λ'/λ, ε_{eff}, and Z_0 and a function of the frequency and also as a function of the distance of separation between the side electric walls (2B) are presented in figures 2 and 3 respectively. Figure 2 shows that for small normalized strip and slot widths, typically $S/D = 0.25$ and $W/D = 0.10$, λ'/λ, ε_{eff}, and Z_0 are almost constant as the frequency varies from 26.5 to 40.0 GHz. However, for large S/D and W/D ratios, typically 5.0 and 1.0 respectively, λ'/λ decreases by 1.5 percent, ε_{eff} increases by 3.0 percent, and Z_0 increases by 5.0 percent with frequency. Figure 3 shows that λ'/λ, ε_{eff}, and Z_0 are constant for all values of S/D and W/D ratios, as 2B varies from about 0.125 in. to an inch. The variation of λ'/λ, ε_{eff}, and Z_0 with respect to frequency in figure 2 are small when compared with the deviations caused by fabrication tolerances alone. Hence, all further computations are carried out at the center frequency of 33 GHz and 2B equal to an inch. Figure 4 presents λ'/λ and ε_{eff} as a function of W/D with S/D as a parameter. Figure 5 presents Z_0 as a function of $S + 2W$ with S/D and W/D as a parameters. The substrate thickness D is assumed to be 100 μm.

Conductor Backed Coplanar Waveguide (CBCPW). - The computed λ'/λ and ε_{eff}, and also Z_0, as a function of W/D with S/D as a parameter are presented in figures 6 and 7, respectively. The substrate thickness D is assumed to be 150 μm in both figures 6 and 7. The computed Z_0, for small values of S/D, is observed to initially increase with W/D and attain a maximum.

Further increase in W/D tends to decrease Z_0. Besides, for large values of S/D, Z_0 is observed to be independent of W/D. An explanation for this is because, for small values of S/D and W/D, the fields are tightly bound to the vicinity of the strip and wave propagation takes place as in a conventional slot-line, with the lower ground plane exerting negligible influence, and hence Z_0 increases with W/D. As W/D increases the upper ground planes begin to decouple and wave guiding takes place as in a conventional microstrip between the strip conductor and the lower ground plane and hence Z_0 decreases.

Suspended Coplanar Waveguide (SCPW). - The computed λ'/λ, ϵ_{eff}, and Z_0 as a function of W/D and with the normalized air gap ratio H/D as a parameter are presented for fixed S/D ratio of 0.25 and 5.0 in figures 8 and 9 respectively. The substrate thickness D is assumed to be 100 µm in both figures 8 and 9. Figure 8 shows that for small S/D ratio of 0.25, λ'/λ increases by 1.2 percent, ϵ_{eff} decreases by 2.4 percent, and Z_0 decreases by 4 percent when W/D = 1.0 and the H/D ratio is decreased from infinity to 0.5. Figure 9 shows that for large S/D ratio of 5.0, λ'/λ increases by 5 percent, ϵ_{eff} decreases by 9 percent, and Z_0 decreases by 23 percent when W/D = 1.0 and H/D ratio is decreased from infinity to 0.5. By comparing Figures 8 and 9 it is observed that the air gap significantly influences the wave propagation on a SCPW with a wide strip conductor when the substrate thickness is 100 µm. Figure 10 illustrates the characteristics when S/D = 2.0 and also the substrate thickness is increased from 100 to 250 µm. It is observed that the air gap plays a very insignificant role and typically λ'/λ increases by 0.35 percent, ϵ_{eff} decreases by 0.7 percent and Z_0 decreases by 5.8 percent when W/D = 1.0 and H/D is reduced from infinity to 0.2. Thus by comparing Figs. 9 and 10 it is observed that when the substrate thickness is increased from 100 to 250 µm the effect of the air gap on the wave propagation is very small. Lastly, from Figs. 8 and 9 it is observed that when H/D is equal to or greater than 5.0, the influence of the lower ground plane on the propagation parameters is negligible and the SCPW characteristics reduce to that of a conventional CPW.

Figure 11 presents λ'/λ and ϵ_{eff} as a function of W/D with S/D as a parameters. Figure 12 presents Z_0 as a function of S + 2W with S/D and W/D as parameters. In these figures the H/D ratio is fixed and equal to unity.

Stripline-like Suspended Coplanar Waveguide (SSCPW). - λ'/λ and ϵ_{eff} as a function of W/D and Z_0 as a function of S + 2W are illustrated in figures 13 and 14 respectively. By comparing figures 4 and 13 it is observed that the λ'/λ ratio is closer to unity and ϵ_{eff} is lower for the SSCPW. This is advantageous, firstly, because circuit dimensions would be larger which in turn would ease fabricational tolerances at mm-wave frequencies. Secondly, more of the electromagnetic field would be concentrated in the air regions which would lower the attenuation.

Inverted Coplanar Waveguide (ICPW). - λ'/λ and ϵ_{eff} as a function of W/D and Z_0 as a function of S + 2W are illustrated in figures 15 and 16 respectively.

B. 50 Ohms Transmission Line Dimensions

Figure 17 compares the strip width and the corresponding slot width that is required for realizing 50 Ω conventional CPW, SCPW, SSCPW, and ICPW transmission lines on 100 μm thick GaAs substrate. It is observed that the suspended structures namely, SCPW, SSCPW, and ICPW require a much wider slot width for a given strip dimension, which is an advantage at mm-wave frequencies.

CONCLUSION

The paper presents three new Suspended Coplanar Waveguide structures namely, SCPW, SSCPW, and ICPW together with their propagation characteristics. The propagation characteristics are graphically illustrated as a function of the slot and strip widths, substrate thickness and permittivity, and the height of the air gap.

These structures have the following advantages over conventional CPW. Firstly, λ'/λ is closer to unity which results in larger dimensions and hence lower tolerances. Secondly, ϵ_{eff} is lower and hence the electromagnetic field energies are concentrated more in the air regions which should lower the attenuation. Thirdly, for a prescribed impedance level, the above structures have a wider slot width for identical strip width. Thus low impedance lines can be achieved with reasonable slot dimensions.

An attractive feature of the ICPW is that it is possible to shunt mount active devices, such as, Gunn and IMPATT diodes between the strip conductor and the metal trough. The metal trough also acting as an efficient heat sink. Finally, it is also possible to construct an E-plane probe-type transition from a rectangular waveguide to SCPW which should find extensive application in the testing of planar active devices and also circuits, such as, GaAs MESFETs and MMICs at mm-wave frequencies.

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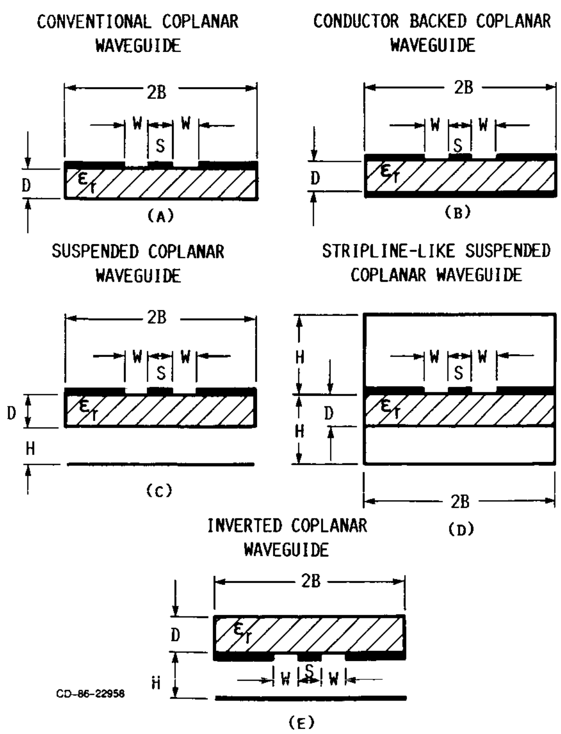

FIGURE 1. - COPLANAR WAVEGUIDE.

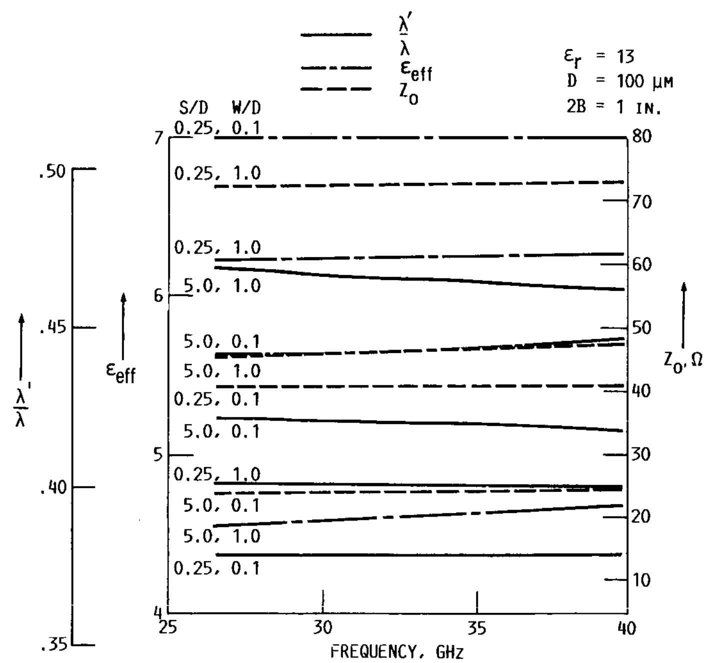

FIGURE 2.- CONVENTIONAL CPW.

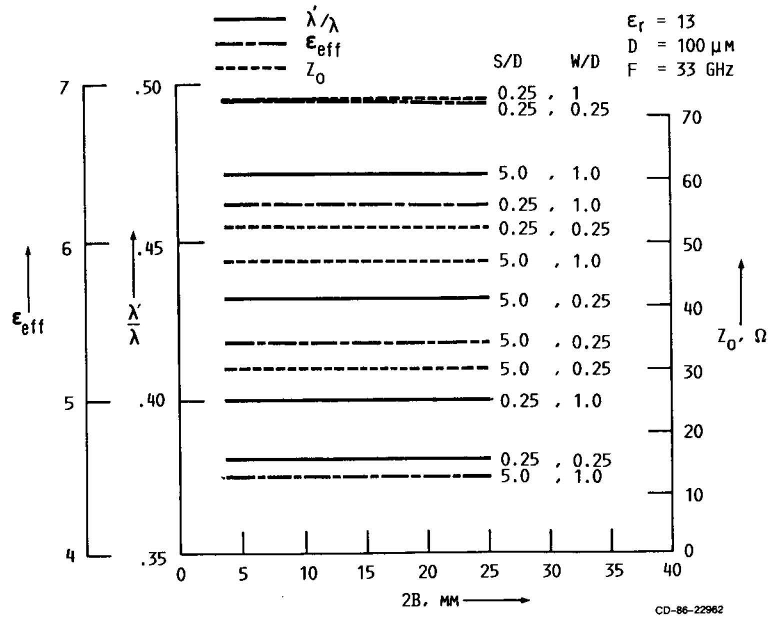

FIGURE 3.- CONVENTIONAL CPW.

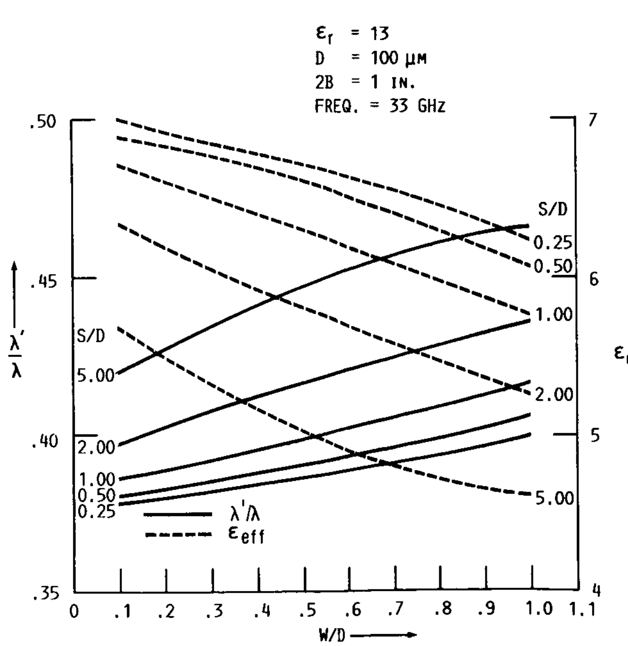

FIGURE 4.- CONVENTIONAL CPW.

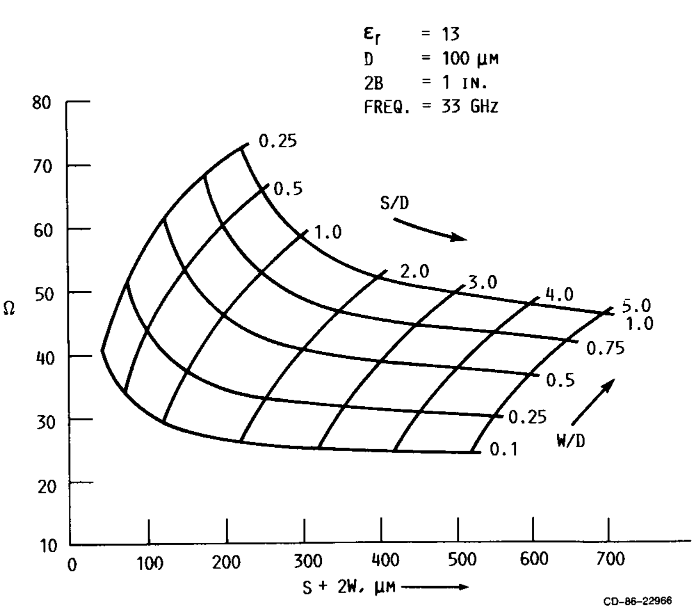

FIGURE 5.- CONVENTIONAL CPW.

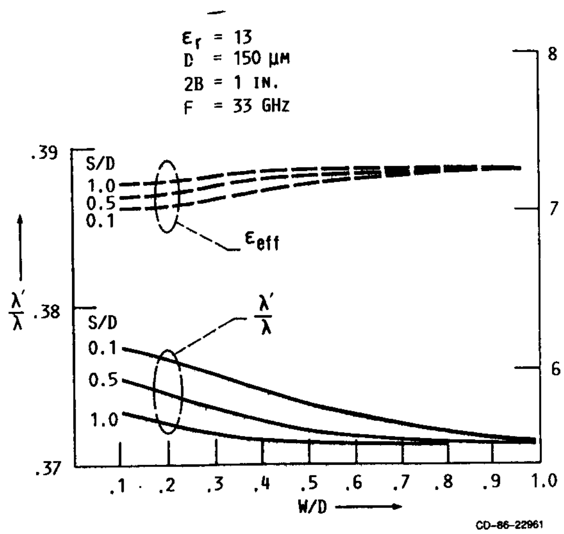

FIGURE 6.- CONDUCTOR BACKED CPW.

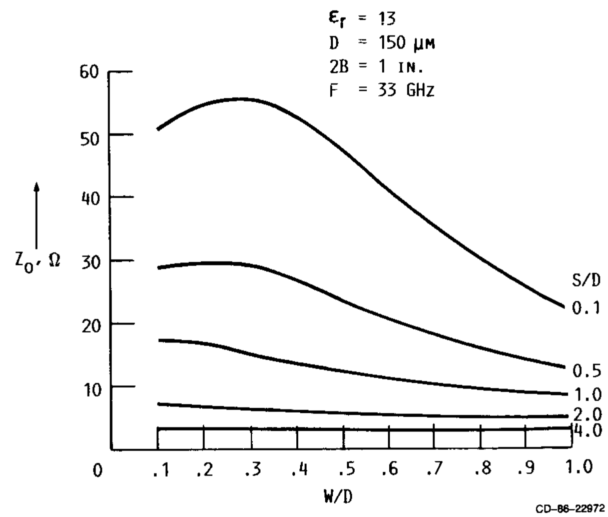

FIGURE 7.- CONDUCTOR BACKED CPW.

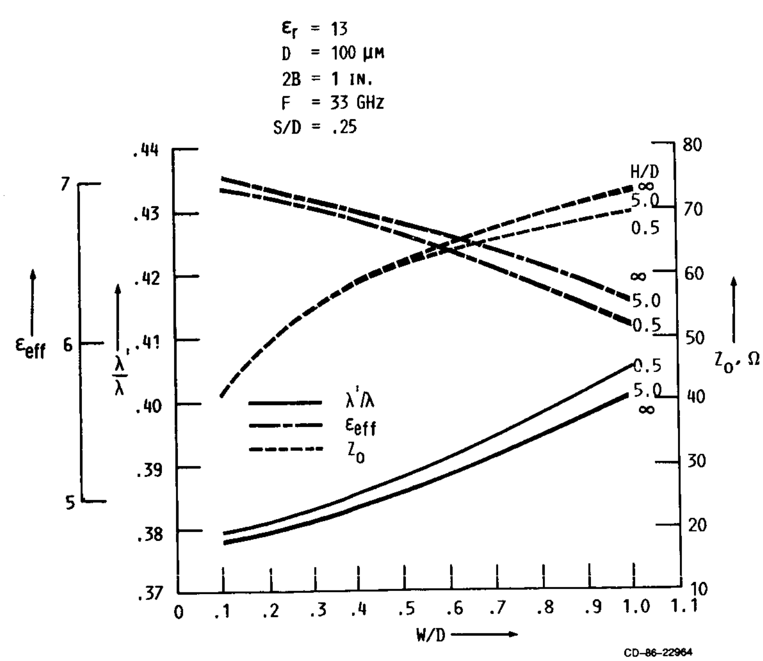

FIGURE 8.- SUSPENDED CPW.

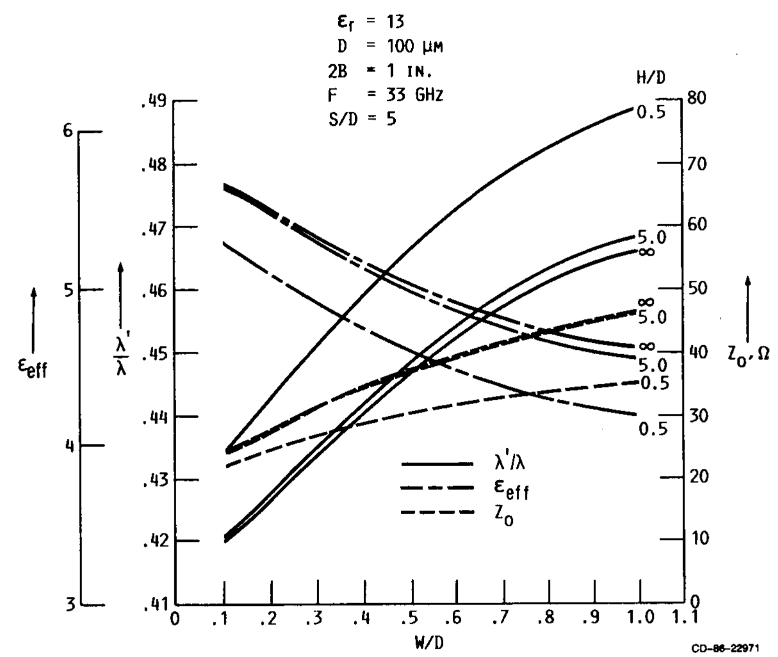

FIGURE 9.- SUSPENDED CPW.

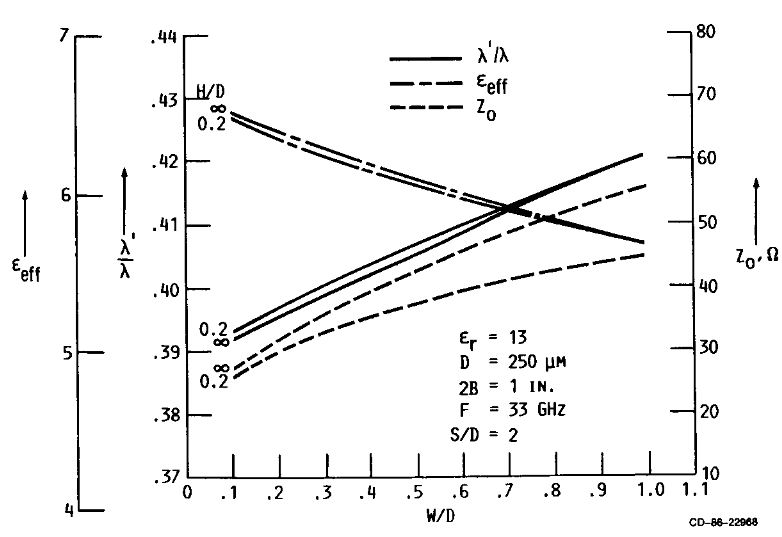

FIGURE 10.- SUSPENDED CPW.

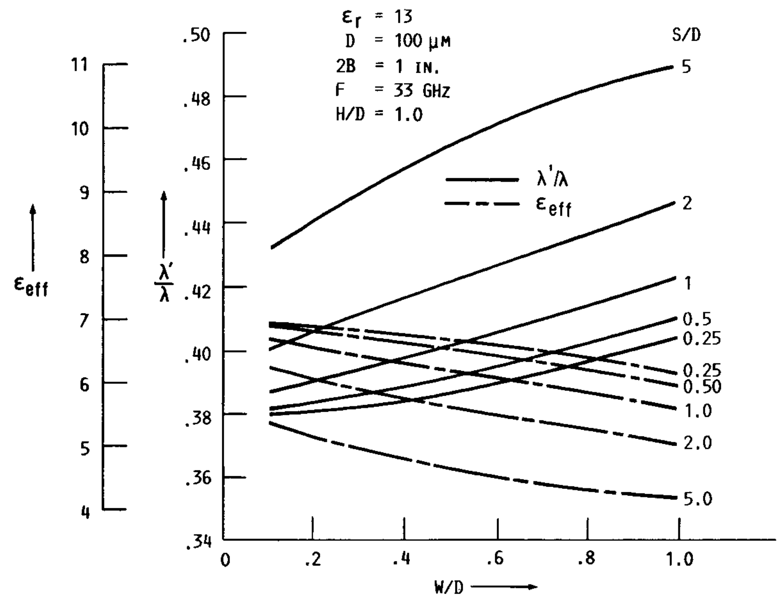

FIGURE 11.- SUSPENDED CPW.

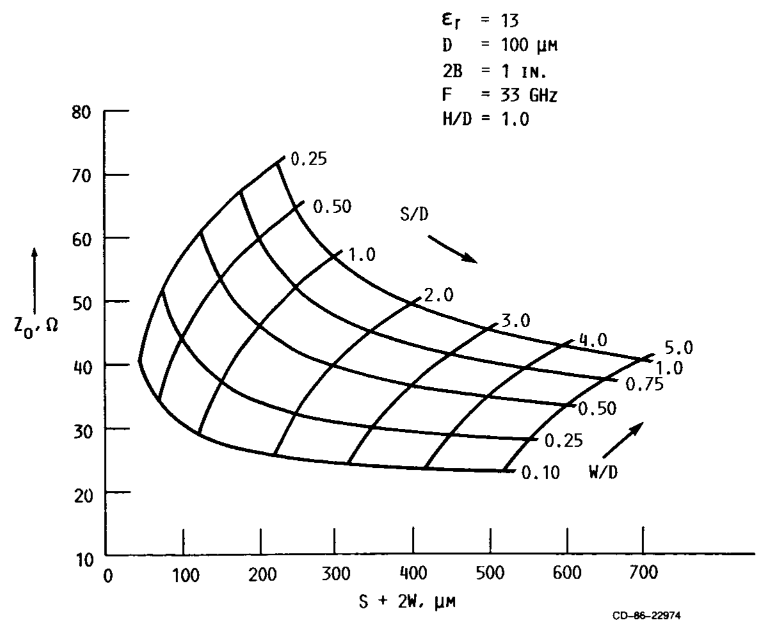

FIGURE 12.- SUSPENDED CPW.

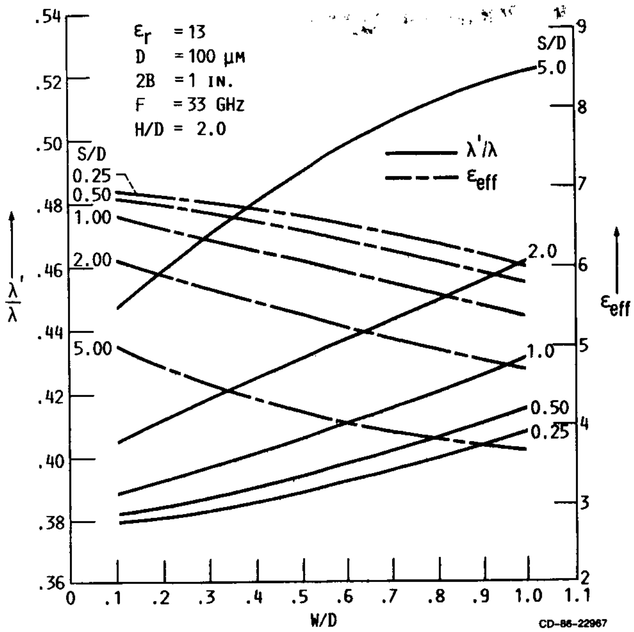

FIGURE 13.- STRIPLINE-LIKE SUSPENDED CPW.

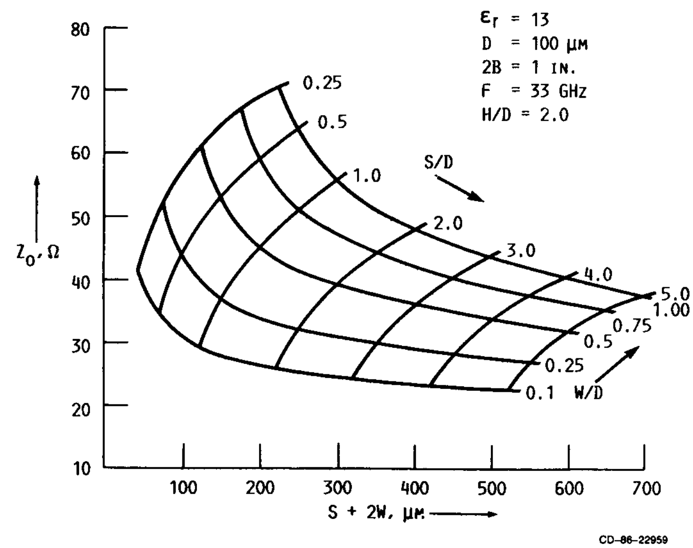

FIGURE 14.- STRIPLINE-LIKE SUSPENDED CPW.

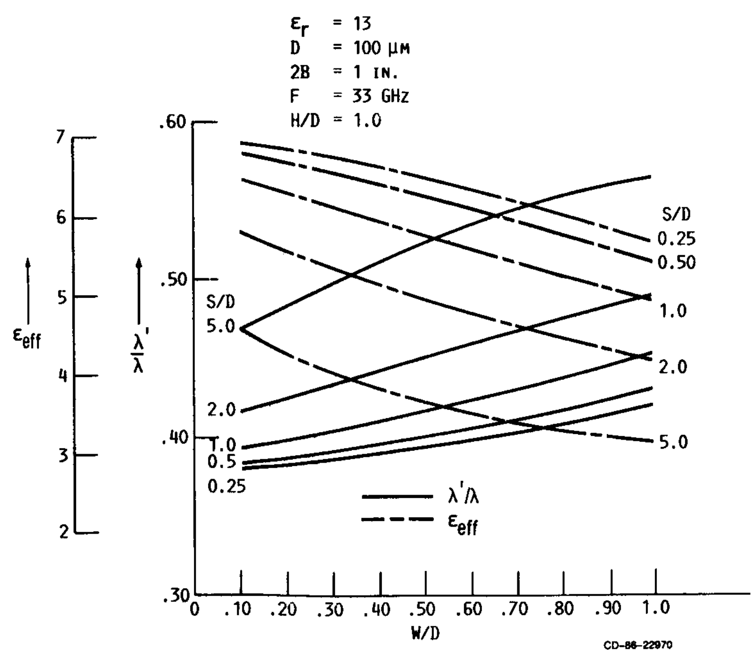

FIGURE 15.- INVERTED CPW.

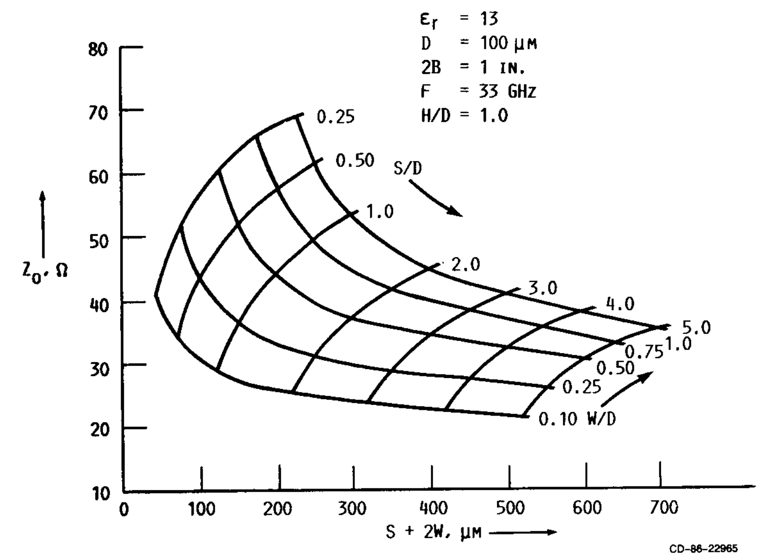

FIGURE 16.- INVERTED CPW.

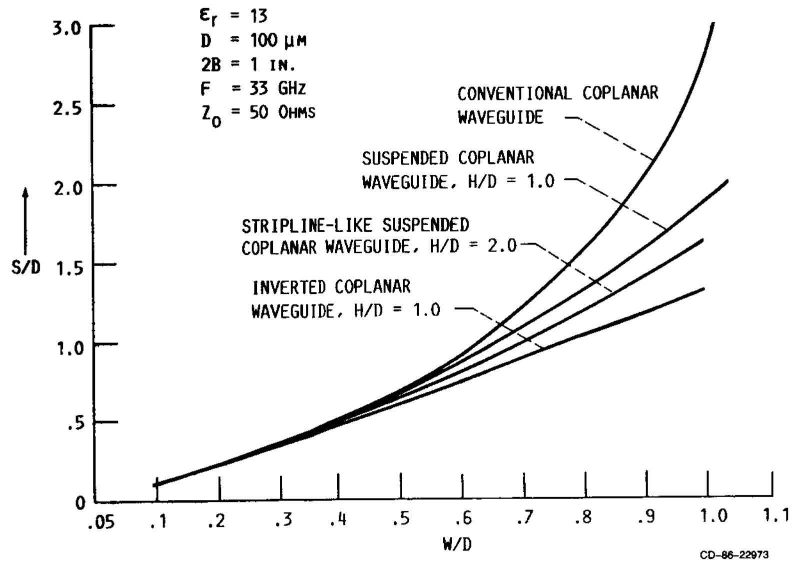

FIGURE 17.- 50 OHMS CPW TRANSMISSION LINES.

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