MEASUREMENT OF SLOT LINE CHARACTERISTICS

E. Mariani, C. Heinzman and J. Agrios
Electronic Components Laboratory
U. S. Army Electronics Command, Fort Monmouth, N. J.

S. B. Cohn, Consultant
Tarzana, California

The development of microwave integrated circuits has effected considerable interest in microstrip transmission lines on dielectric substrates. This paper discusses the slot line, a novel transmission line that may be used in association with, or as an alternative to microstrip. Slot line consists of a narrow slot in a thin conductive layer on one side of a high permittivity dielectric substrate; the other side is bare as shown in Fig. 1. The slot line offers some important advantages when compared to microstrip by virtue of the slot-mode configuration, Fig. 2. The electric field is across the slot while the magnetic field is perpendicular to the slot and forms closed loops at half-wave intervals. Thus, the slot line possesses a region of elliptical polarization which should be useful for constructing a variety of non-reciprocal, ferrite, slot line devices such as resonance isolators, latching phase shifters, and circulators. Since the slot mode's voltage occurs across the slot on one side of the substrate, it is especially convenient for connecting shunt elements such as diodes, resistors and capacitors. Moreover, the same manufacturing techniques used for microstrip integrated circuits can be applied to slot line.

NOTES

The slot line utilizes a dielectric substrate of sufficiently high permittivity such that the fields are closely confined to the slot and the slot-mode wavelength, λ' , will be substantially less than the free-space wavelength with negligible radiation loss.

The results of a second-order analysis are graphically described in Figures 3, 4, and 5; the following parameters are presented as a function of slot width (W), substrate thickness (D), permittivity (ϵr), and frequency: (1) relative wavelength ratio, λ'/λ (λ' = slot mode wavelength, λ = free-space wavelength); and (2) characteristic impedance, Z_o. It may be observed that the λ'/λ curves for the different W/D ratios converge in the neighborhood of a value of D/λ. The point of convergence is close to the zero-order solution and it occurs approximately when the thickness of the substrate, D, is $\lambda_d/4$, where λ_d is the wavelength in the dielectric. For larger D/λ ratios, surface waves are likely to be troublesome and Figures 3, 4, and 5 do not reflect any calculations for such values of D/λ .

In order to verify the theoretical values of λ'/λ *, several slot line circuits were fabricated using three Custom Material, Inc. substrate materials. The dielectric constants of these substrate materials were experimentally determined to be 20.3, 14.5, 13.2. The slot transmission lines were fabricated in two ways. First, one side of the dielectric substrate was covered with 3M Co. Scotch Brand No. 51 aluminum sensing tape,

* The computer program to calculate various slot line characteristics was devised by Dr. E. G. Cristal of SRI under a program sponsored by the U. S. Army Electronics Command, Fort Monmouth, N. J., Contract No. DAAB07-68-C-0088.

0.625 inches wide and 0.0008 inches thick including adhesive. Slots of various widths were formed by leaving an appropriate gap along the center line of the substrate face. Also, the substrate materials were electroless plated by the Shipley Method and then electroplated so that the total copper thickness was approximately 0.0008 inches. The slot transmission line was formed by etching a narrow slot along the full length of one face while the copper was removed from all other surfaces. Slot lines four or five inches long were investigated.

An electric probe terminating a reflectometer directional coupler was coupled to one end of the slot. The slot length was varied by sliding a thin steel scale (calibrated in 1/100th of an inch) over the slot from the end opposite the probe; resonance was indicated by a dip in the reflected wave. At each test frequency the overlapping length of the scale was varied until resonance was found and the scale was accurately read relative to a reference point. As many half-wave lengths, $\lambda'/2$, were obtained as possible for each frequency. From these measurements the experimental values of λ'/λ were computed and compared to the theoretical data for λ'/λ ; Tables 1 through 4 compare the experimental and theoretical data for for the various dielectric substrates measured:

TABLE 1

λ'/λ DATA USING ALUMINUM SENSING TAPE

Er = 13.2   d = 0.065"

	Freq-MHz	Exp. λ'/λ	Theor. λ'/λ	% Error
	2.180	0.489	0.468	+4.5%
W = 0.027" ± .001"	2.613	0.486	0.460	+5.6%
W/D = 0.42	3.019	0.479	0.454	+5.5%
	3.580	0.476	0.447	+6.5%
	3.952	0.462	0.441	+4.8%
	2.112	0.505	0.480	+5.2%
W = 0.035" ± .001"	2.500	0.501	0.471	+6.4%
W/D = 0.54	3.077	0.486	0.461	+5.4%
	3.644	0.478	0.453	+5.5%
	4.000	0.474	0.447	+6.0%
	2.090	0.524	0.496	+5.6%
W = 0.051" ± .001"	2.598	0.512	0.484	+5.8%
W/D = 0.78	2.963	0.503	0.477	+5.5%
	3.454	0.493	0.468	+5.3%
	3.780	0.485	0.463	+4.8%

TABLE 2

λ'/λ DATA USING ALUMINUM SENSING TAPE

Er = 14.5   d = 0.069"

	Freq-MHz	Exp. λ'/λ	Theor. λ'/λ	% Error
	2215	0.457	0.441	+3.6%
	2508	0.456	0.436	+4.6%
W = .025" ± .001"	2896	0.448	0.430	+4.2%
W/D = 0.36	3141	0.444	0.426	+4.2%
	3433	0.441	0.422	+4.5%
	3800	0.432	0.418	+3.3%
	2306	0.472	0.459	+2.8%
W = .044" ± .001"	2791	0.463	0.449	+3.1%
W/D = 0.64	3254	0.455	0.441	+3.2%
	3913	0.445	0.431	+3.2%
	2.106	0.486	0.473	+2.8%
	2.346	0.475	0.467	+1.7%
W = .055" ± .002"	2.651	0.472	0.461	+2.4%
W/D = 0.80	3.052	0.464	0.453	+2.4%
	3.304	0.457	0.448	+2.2%
	3.967	0.448	0.437	+2.5%

Table 3

λ'/λ DATA USING ALUMINUM SENSING TAPE

Er = 20.3   d = 0.137"

	Freq-MHz	Exp. λ'/λ	Theor. λ'/λ	% Error
	2150	0.351	0.341	+2.9%
W = .027" ± .002"	2600	0.347	0.335	+3.6%
W/D = 0.20	3000	0.341	0.329	+3.6%
	3400	0.337	0.324	+4.0%
	3850	0.331	0.320	+3.4%
W = .051" ± .002"	2000	0.355	0.351	+1.1%
W/D = 0.37	2500	0.347	0.341	+1.7%
	3000	0.336	0.332	+1.2%
	3800	0.326	0.321	+1.6%
	2204	0.356	0.355	+0.3%
W = .073" ± .002"	2788	0.343	0.343	0%
W/D = 0.53	3062	0.336	0.338	-0.6%
	3403	0.333	0.332	+0.3%
	3844	0.327	0.325	+0.6%
W = .100" ± .002"	2595	0.353	0.352	+0.3%
W/D = 0.73	3434	0.334	0.335	-0.3%
	3860	0.330	0.327	+0.9%

TABLE 4

λ'/λ DATA USING PLATED SUBSTRATES

Er = 20.3   d = 0.137"

	Freq-MHz	Exp. λ'/λ	Theor. λ'/λ	% Error
	2119	0.341	0.341	0%
W = .024" ± .001"	2475	0.332	0.336	-1.2%
W/D = 0.18	2984	0.322	0.329	-2.1%
	3331	0.323	0.325	-0.6%
	3773	0.314	0.320	-1.9%

Er = 14.5   d = 0.069"

	Freq-MHz	Exp. λ'/λ	Theor. λ'/λ	% Error
	2215	0.438	0.441	-0.7%
	2508	0.431	0.436	-1.1%
W = .024" ± .002"	2896	0.424	0.430	-1.4%
W/D = 0.35	3141	0.421	0.426	-1.2%
	3434	0.414	0.422	-1.9%
	3790	0.410	0.418	-1.9%

Er = 13.2   d = 0.065"

	Freq-MHz	Exp. λ'/λ	Theor. λ'/λ	% Error
	2197	0.479	0.463	+3.5%
W = .023 ± .002"	2598	0.469	0.456	+2.9%
W/D = 0.35	2963	0.465	0.450	+3.3%
	3454	0.459	0.444	+3.4%
	3775	0.453	0.439	+3.2%

It is apparent from the data presented in Tables 1 through 4 that the experimental results achieved with the aluminum sensing tape were strongly affected by the thin adhesive backing whereby the effective dielectric constant of the substrate was reduced from the measured value of ϵ_r causing the λ'/λ ratio to increase with respect to the theoretical value. Also, the adhesive had a larger effect on the substrates of lower dielectric constant, as expected. The experimental results compare very well to the theoretical for the case of the plated substrates. It appears that better agreement is achieved with the higher dielectric constant substrates. The remaining discrepancy is believed due to the slight inaccuracies in the measured ϵ_r, dimensional tolerance of the slot width, slight variations in the substrate thickness, and experimental error.

Measurement of the slot line characteristic impedance, Z_o, has not been accomplished at this time; however, work is currently in progress. The theoretical results that have been computed are presented in Figures 3, 4, and 5.

The theoretical analysis has also been extended to the "slot-line sandwich" case. This is the case where another dielectric substrate is placed on top of the slot, thereby decreasing the wavelength further. The analysis will be forthcoming in the very near future.

References:

1. S. B. Cohn, "Slot-Line - An Alternative Transmission Medium for Integrated Circuits". IEEE G-MTT International Microwave Symposium Digest, pp 104-109 (May 1968).

2. D. K. Adams, E. G. Cristal, S. B. Cohn, R. Y. Ho, "Microwave Synthesis Techniques". Contract No. DAAB07-68-C-0088, Annual Report (September 1968) and Semi-Annual Report (February 1969).

3. S. B. Cohn, "Slot-Line on a Dielectric Substrate". Submitted for publication to IEEE Trans. Microwave Theory and Techniques.

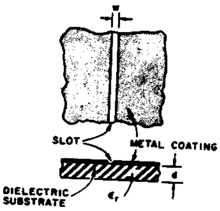
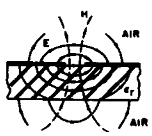
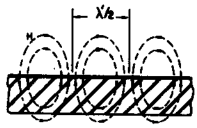


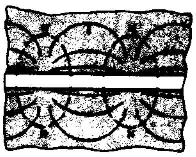
FIG. 1 SLOT LINE ON A DIELECTRIC SUBSTRATE



(a) FIELD DISTRIBUTION IN CROSS-SECTION



(b) H FIELD IN LONGITUDINAL SECTION



(c) CURRENT DISTRIBUTION ON METAL SURFACE

FIG. 2 FIELD AND CURRENT DISTRIBUTION

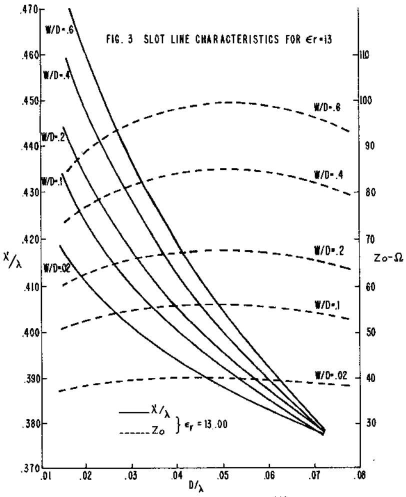


FIG. 3 SLOT LINE CHARACTERISTICS FOR Єr=13
W/D=.6
W/D=.4
W/D=.2
W/D=.1
W/D=.02
X/λ
Zo-Ω
D/λ
—— X/λ
----- Zo } єr = 13.00

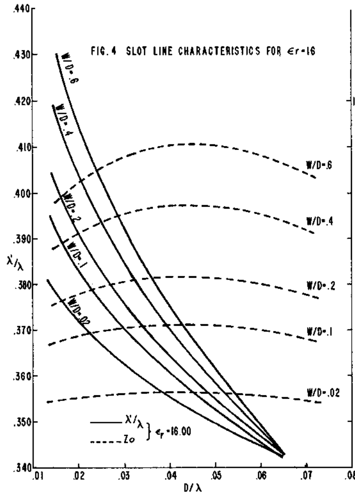


FIG. 4 SLOT LINE CHARACTERISTICS FOR Єr=16
W/D=.6
W/D=.4
W/D=.2
W/D=.1
W/D=.02
X/λ
Zo-Ω
D/λ
—— X/λ
----- Zo } єr =16.00

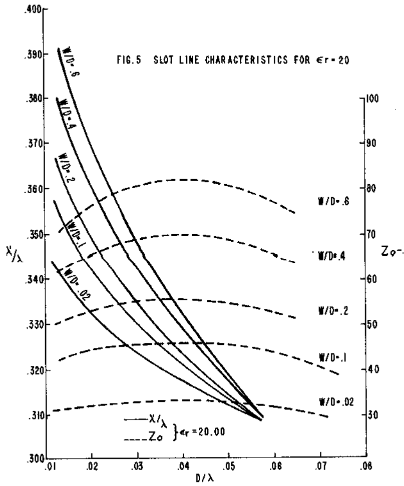


FIG. 5 SLOT LINE CHARACTERISTICS FOR Єr=20
W/D=.6
W/D=.4
W/D=.2
W/D=.1
W/D=.02
X/λ
D/λ
—— X/λ
---- Zo } єr =20.00