experimental data. Such couplers are useful for sensing the power of an airborne transponder and for other communication applications. The results are useful for the design of a well-matched multiaperture directional coupler between stripline and microstripline.

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Additional Approximate Formulas and Experimental Data on Micro-Coplanar Striplines

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Abstract —**Additional approximate design formulas and experimental data of micro-coplanar striplines, which have recently been proposed for high-packing-density MMIC's, are given in this paper to be applied to four types of substrate materials: GaAs, plastics, and alumina with different dielectric constants.**

I. INTRODUCTION

In connection with the design of high-packing-density microwave monolithic integrated circuits (MMIC's), Pucel has discussed the necessity of solutions for two types of proximity effects [1]. One type is observed between the microstrip conductor and closely located conductor having ground potential on the top of the same substrate [2]. The other type occurs when microstrip lines are near a substrate edge [3].

The former effects have been analyzed by one of the authors [2] and the effects of the location of the upper ground conductor on the characteristics of the microstrip lines have been discussed. The micro-coplanar stripline (MCS) structure, shown in Fig. 1, has been proposed as a measure to avoid this type of proximity effect. Namely, the structural dimensions of micro-coplanar striplines are so designed that the characteristic impedance is kept at a constant value even when the ground potential conductor is located close to the strip conductor. With this structure, the packing density of MMIC's can be enhanced, and shunt element connection between the strip conductor and the upper ground conductor can be easily realized.

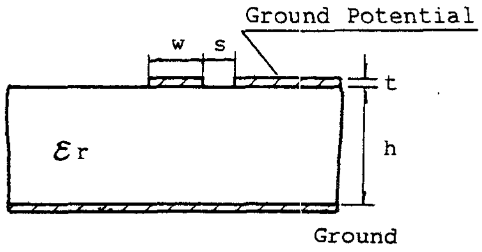

Fig 1 Cross-sectional view of micro-coplanar striplines.

In this paper, we present several approximate design formulas of MCS's in addition to previous ones [2] assuming the use of other substrate materials with different dielectric constants. The analysis is based on the rectangular boundary division method given in the previous paper [2]. These approximate formulas are derived by applying a least-square curve-fitting procedure to the results of our computation. Experimental data on the MCS's with an alumina substrate are also compared with theoretical values.

II. DESIGN FORMULAS OF MCS'S FOR DIFFERENT SUBSTRATE MATERIALS

The design procedures of the MCS's consist of finding the strip width (w) for keeping the characteristic impedance at 50 Ω against specified values of separation (s), the subsequent guide wavelength (λ) of such 50 Ω MCS's, and preferably, their conductor attenuation constant (α_c). Since theoretical derivations of relevant expressions are the same as those in the previous paper [2], they are not repeated here. Our numerical computation covers four types of substrate materials in current use, namely, GaAs ($\epsilon_r = 12.9$), plastics ($\epsilon_r = 2.22$), and two kinds of alumina (ϵ_r values of 9.7 and 10.1). To simplify the expressions, the calculated results of w, λ, and α_c are normalized by w_0 (the strip width of the 50 Ω microstrip line), λ_0 (free-space wavelength), and $\sqrt{f/f_0}$ respectively. Here f_0, the frequency for the numerical estimation of the attenuation constant, is taken as 10 GHz, and f is the frequency to be used.

Using a least-square curve-fitting procedure, all the theoretical data of w/w_0, λ/λ_0, and $\sqrt{f/f_0}\,\alpha_c$ are expressed in simple polynomial formulas as follows:

$$\frac{w}{w_0} = \sum_{i=0}^{M} a_{0i} u^i + \left(\frac{t}{h}\right) \sum_{i=0}^{M} a_{1i} u^i \tag{1}$$

$$\frac{\lambda}{\lambda_0} = \sum_{i=0}^{N} b_{0i} u^i + \left(\frac{t}{h}\right) \sum_{i=0}^{N} b_{1i} u^i \tag{2}$$

and

$$\sqrt{f/f_0}\,\alpha_c = \sum_{i=0}^{P} C_{0i} u^i + \ln\left(\frac{t}{h}\right) \sum_{i=0}^{P} C_{1i} u^i + \left[\ln\left(\frac{t}{h}\right)\right]^2 \sum_{i=0}^{P} C_{2i} u^i \tag{3}$$

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TABLE I
COEFFICIENTS IN THE DESIGN FORMULAS OF MICRO–COPLANAR STRIPLINES

Substrate	GaAs (ε_r=12.9)	Plastics (ε_r=2.22)		Alumina (ε_r=9.7)		Alumina (ε_r=10.1)
h(μm)	$100<h<200$	254	127	635	380	400
t(μm)	2	$17.5<t<35$	$17.5<t<35$	$2<t<5$	$3<t<5$	$2<t<5$
M,N	5,3	3,2	3,2	4,2	4,2	4,2
a_{00}	.89631	.99960	.99912	.94360	.94614	.94229
a_{01}	.16995	$.14323\times10^{-1}$	$.12805\times10^{-1}$	.10316	.10933	.11272
a_{02}	$-.69075\times10^{-1}$	$-.11455\times10^{-1}$	$-.10867\times10^{-1}$	$-.56725\times10^{-1}$	$-.55529\times10^{-1}$	$-.59603\times10^{-1}$
a_{03}	$-.78411\times10^{-2}$	$.22587\times10^{-2}$	$.23232\times10^{-2}$	$.26502\times10^{-2}$	$.26287\times10^{-3}$	$.13959\times10^{-2}$
a_{04}	$-.45987\times10^{-2}$	.00000	.00000	$.31846\times10^{-2}$	$.24353\times10^{-2}$	$.34819\times10^{-2}$
a_{05}	$.71210\times10^{-3}$	.00000	.00000	.00000	.00000	.00000
a_{10}	-.42781	$-.22312\times10^{-2}$	$-.42684\times10^{-2}$	.11123	-.36115	-.45730
a_{11}	.51532	$.90593\times10^{-2}$	$.28201\times10^{-1}$	.95333	.15528	.65467
a_{12}	$-.96986\times10^{-1}$	$-.33336\times10^{-1}$	$-.70588\times10^{-1}$	-.35162	-.42619	- 33073
a_{13}	$.82001\times10^{-2}$	$.13641\times10^{-1}$	$.27036\times10^{-1}$	-.44937	.23626	$.26881\times10^{-1}$
a_{14}	$.33134\times10^{-2}$	.00000	.00000	$-.62438\times10^{-2}$	$.80691\times10^{-1}$	$.13609\times10^{-1}$
a_{15}	$-.78121\times10^{-1}$	.00000	.00000	.00000	.00000	.00000
b_{00}	.35620	.72875	.72923	.40144	.40081	.39358
b_{01}	$.98750\times10^{-2}$	$-.38051\times10^{-2}$	$-.32397\times10^{-2}$	$-.64388\times10^{-2}$	$-.65335\times10^{-2}$	$-.67951\times10^{-2}$
b_{02}	$.81594\times10^{-3}$	$.12219\times10^{-2}$	$.12535\times10^{-2}$	$.96598\times10^{-3}$	$.99237\times10^{-3}$	$.14451\times10^{-2}$
b_{03}	$.75375\times10^{-3}$	.00000	.00000	.00000	.00000	.00000
b_{10}	.21331	$.12655\times10^{-1}$	$.21859\times10^{-1}$	.13182	.13917	.20730
b_{11}	$.82700\times10^{-1}$	$-.12009\times10^{-1}$	$-.27980\times10^{-1}$	-.13143	-.15370	-.13590
b_{12}	.11323	$.84954\times10^{-2}$	$.16751\times10^{-1}$	$.91950\times10^{-1}$	$.92805\times10^{-1}$	$.49911\times10^{-1}$
b_{13}	$.73125\times10^{-1}$	.00000	.00000	.00000	.00000	.00000

where h is the substrate thickness, t is the strip thickness, and w_0 and u are given by

$$w_0 = d_0 + d_1 \ln(t/h) + d_2[\ln(t/h)]^2 \tag{4}$$

and

$$u = \ln(s/w_0) \qquad (0.1 < s/w_0 < 10).$$

The coefficients, a_{ji}, b_{ji}, c_{ji}, and d_j, of the above formulas are listed in Table I and Table II for the aforementioned four types of substrate materials.

Proper orders of the polynomials (M, N, and P) have been selected in the above expressions to ensure that the discrepancy between values obtained from these approximate formulas and those derived from a rigorous theoretical analysis is less than 1%. Because the theoretical values of the characteristic impedance and guide wavelength themselves have errors of about 1% due to the nature of the variational method [4], the total errors of the above approximate formulas should be 2% or less.

III. EXPERIMENTAL CHARACTERIZATION OF MCS'S

To prove the validity of our analysis method and design formulas, basic experiments have been carried out to characterize a few MCS's fabricated in a laboratory. Three samples of MCS's on 400-μm-thick alumina substrate ($\epsilon_r = 10.1$) have been selected, with the separation, s, between the central strip and conductor of ground potential being 300 μm, 100 μm, and 50 μm for each sample. Also a conventional microstrip line ($s = \infty$) was fabricated for comparison.

The characteristic impedances, Z, of these MCS's were measured with the time-domain reflectometer (TDR) method using an HP8510B network analyzer, while the guide wavelength ratio, λ/λ_0, was obtained by measuring the S_{21} phase angle with an

TABLE II
COEFFICIENTS IN THE DESIGN FORMULAS OF MICRO–COPLANAR STRIPLINES (CONTINUED)

Substrate	GaAs (ε_r=12.9)	Plastics (ε_r=2.22)		Alumina (ε_r=9.7)		Alumina (ε_r=10.1)
h(μm)	$100<h<200$	254	127	635	380	400
t(μm)	2	$17.5<t<35$	$17.5<t<35$	$2<t<5$	$3<t<5$	$2<t<5$
P	5	4	5	4	4	5
c_{00}	$.41779\times10^{+1}$	$.33812\times10^{-1}$	$.67622\times10^{-1}$	$.34048\times10^{-1}$	$.54375\times10^{-1}$	$.71327\times10^{-1}$
c_{01}	-.92425	$.86822\times10^{-3}$	$-.11516\times10^{-2}$	$-.14982\times10^{-2}$	$-.54119\times10^{-2}$	$-.31487\times10^{-1}$
c_{02}	$.12991\times10^{+1}$	$.58640\times10^{-3}$	$.12193\times10^{-2}$	$.53392\times10^{-2}$	$.85379\times10^{-2}$	$-.19138\times10^{-2}$
c_{03}	-.71947	$-.16678\times10^{-2}$	$-.19403\times10^{-2}$	$-.23201\times10^{-2}$	$-.50485\times10^{-2}$	$-.95828\times10^{-2}$
c_{04}	$-.96455\times10^{-1}$	$.55043\times10^{-3}$	$.15802\times10^{-2}$	$.32312\times10^{-3}$	$.10918\times10^{-2}$	$.97879\times10^{-2}$
c_{05}	$.95165\times10^{-1}$	.00000	$-.38592\times10^{-3}$	.00000	.00000	$-.14676\times10^{-2}$
c_{10}	$.14833\times10^{+1}$	$-.32703\times10^{-2}$	$-.65208\times10^{-2}$	$-.43852\times10^{-2}$	$-.79009\times10^{-2}$	$-.19948\times10^{-3}$
c_{11}	-.29318	$.26819\times10^{-3}$	$-.20362\times10^{-3}$	$.16233\times10^{-2}$	$.22403\times10^{-2}$	$-.75294\times10^{-2}$
c_{12}	.52295	$-.23411\times10^{-4}$	$-.43010\times10^{-4}$	$-.58317\times10^{-3}$	$-.10887\times10^{-2}$	$-.57930\times10^{-2}$
c_{13}	-.31241	$-.22304\times10^{-3}$	$-.26785\times10^{-3}$	$.30403\times10^{-3}$	$.27365\times10^{-3}$	$-.25082\times10^{-2}$
c_{14}	$-.54047\times10^{-1}$	$.83667\times10^{-4}$	$.40890\times10^{-3}$	$-.72987\times10^{-4}$	$-.11987\times10^{-4}$	$.37394\times10^{-2}$
c_{15}	$.47012\times10^{-1}$	.00000	$-.11824\times10^{-3}$	.00000	.00000	$-.52786\times10^{-3}$
c_{20}	.13660	.00000	.00000	.00000	.00000	$.83068\times10^{-3}$
c_{21}	$-.23435\times10^{-1}$	.00000	.00000	.00000	.00000	$-.10120\times10^{-2}$
c_{22}	$.54638\times10^{-1}$	.00000	.00000	.00000	.00000	$-.51419\times10^{-3}$
c_{23}	$-.34692\times10^{-1}$	.00000	.00000	.00000	.00000	$-.33020\times10^{-3}$
c_{24}	$-.70373\times10^{-2}$	.00000	.00000	.00000	.00000	$.40611\times10^{-3}$
c_{25}	$.56996\times10^{-2}$	.00000	.00000	.00000	.00000	$-.54824\times10^{-4}$
d_0	636.58	710.47	333.68	582.57	346.71	354.32
d_1	355.59	-22.389	-18.16	-5.6435	-4.0874	-3.3102
d_2	53.962	.00000	.00000	.00000	.00000	.00000

TABLE III
COMPARISON OF MEASURED VALUES WITH CALCULATED VALUES OF TRANSMISSION CHARACTERISTICS OF MICRO–COPLANAR STRIPLINES

Sample Dimensions		s(μm)	MS Line	296	95	46
		w(μm)	382	375	374	374
Z(Ω)	Calculated		49.22	47.52	42.26	38.25
	Measured		50.93	48.28	43.05	40.06
λ/λ_0	Calculated		0.387	0.396	0.406	0.412
	Measured		0.385	0.393	0.397	0.399

Other parameters: $\epsilon_r = 10.1$, $h = 400$ μm, $t = 5$ μm.

HP8753A at 1.5 GHz. The experimental results, including unavoidable errors, are listed in Table III for comparison with the calculated results. Maximum differences of the characteristic impedance and the guide wavelength ratio are found to be within 5% and 2%, respectively, in these experimental data.

IV. USABLE FREQUENCIES LIMITED BY THE TEM-WAVE APPROXIMATION

Since the rectangular boundary division analysis is based on the TEM-wave approximation, there exists a limitation on usable frequencies for this structure, beyond which the dispersion effects can no longer be neglected. The amount of tolerable deviation of guide wavelength depends on the designer's requirements. An approximate dispersion formula of microstrip lines developed by one of the authors [5], though not a rigorous one for the present MCS structure, is applied here to approximate the upper limit of the usable frequencies. We define the factor δ as the deviation of

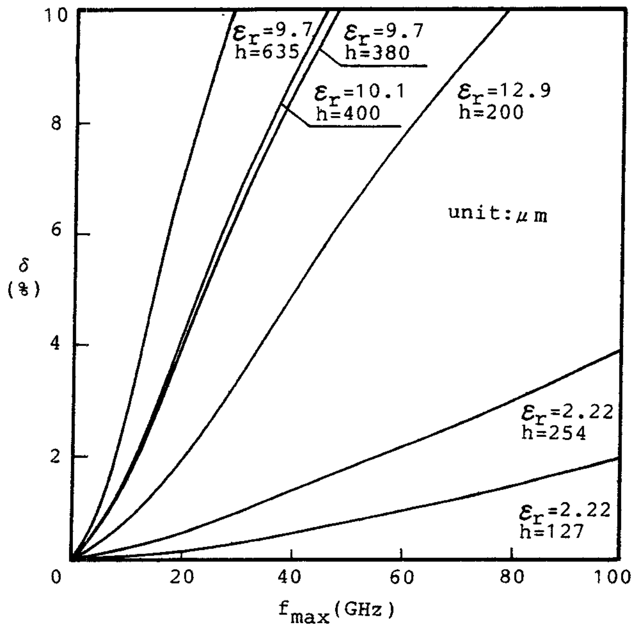

Fig. 2. The deviation factor of guide wavelength, δ, versus the maximum usable frequency, f_{max}.

the guide wavelength obtained with TEM-wave approximation, λ_{TEM}, from the actual guide wavelength, λ. Then the maximum usable frequency, f_{max}, for a given value of δ can be expressed as follows:

$$f_{max} = \frac{c \cdot \eta}{4h\sqrt{\epsilon_r - 1}\left\{0.5 + \left[1 + 2\log_{10}(1 + w/h)\right]^2\right\}} \tag{5}$$

where

$$\eta = \left(\frac{1-\delta}{4\delta}\sqrt{\epsilon_r} \cdot \frac{\lambda_{TEM}}{\lambda_0} - \frac{1}{4\delta}\right)^{-0.667} \tag{6}$$

and

$$\delta = \frac{\lambda_{TEM} - \lambda}{\lambda_{TEM}} \tag{7}$$

and c is the velocity of light in vacuum.

The relationships between the tolerable deviation factor, δ, and the maximum usable frequency, f_{max}, are shown in Fig. 2. This frequency can be regarded as an upper limit, under which the approximate formulas presented in this paper can be used within a specific degree of tolerance for dispersion.

V. Conclusion

Design parameters of micro–coplanar striplines on a variety of substrate materials have been calculated with the rectangular boundary division method. After a least-square curve-fitting procedure, a group of approximate formulas has been obtained for practical use in the design of this new type of transmission line. Experimental data were presented for comparison with theoretical results.

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Reflection of Electromagnetic Waves from Rough Waveguides

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Abstract —**The reflection coefficient of a section of randomly rough waveguide is calculated by using a coordinate transformation developed by Mallick and Sanyal. We perform a perturbation analysis, assuming that the amplitude of the roughness is small compared to the average width of the waveguide. A drastic difference at long wavelengths between TEM on the one hand and TE and TM on the other has been found.**

I. Introduction

The effects of surface roughness on the propagation of electromagnetic waves is important in the fields of precision microwave measurements and standards [1]. Roughness also partly determines the properties of the waveguides and the Q factor of resonant cavities [2]. Previous work on rough waveguides has focused on the limit where the width of the waveguide varies slowly along its length [3], [4]. Much work has also been performed on periodic corrugation of waveguides [1], [5] and on scattering from random surfaces [6]. Physically the problem has some similarity to the propagation of elastic waves (phonons) down narrow wires [7].

In this paper we will calculate the effects of roughness on the reflection coefficient of a section of waveguide. Decomposition into modes is achieved by utilizing a coordinate transformation analogous to that developed by Mallick and Sanyal [5]. The significance of the coordinate transformation is that the bounding, rough surface becomes a surface of constant coordinate, facilitating the application of the boundary conditions. The problem reduces to a one-dimensional form, where we may use a perturbation approach to deduce the reflection coefficient.

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