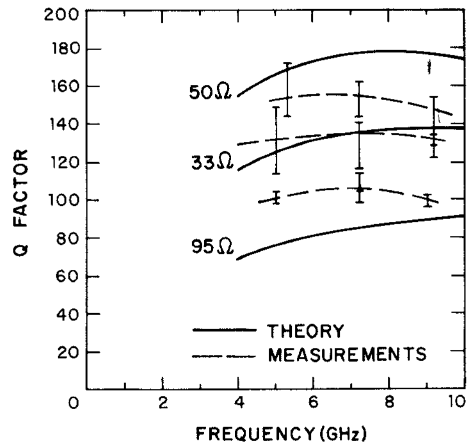

Fig. 5. Half-wavelength resonator quality factor plotted against frequency for resonators on substrates with $\epsilon_r = 13.0$, thickness 0.635 mm, and ground-plane spacing $2b = 1.2$ mm.

conductor loss curve is given in Fig. 4, and from this, conductor losses for any ground-plane spacing may be obtained.

Quality factors of $\lambda_g/2$ resonators were calculated for $\epsilon_r = 13.0$ substrate, 0.635 mm thick, and ground plane spacing of 1.2 mm. Experimental measurements were performed on open-circuit resonators on Trans Tech D-13 substrates 0.635 mm thick for this ground-plane spacing of 1.2 mm. To extract the unloaded Q, the loss in the feed line was also taken into account in the usual manner. The comparison between theory and experiment is shown in Fig. 5, where the best agreement is for the 33-Ω resonators. Measurements of the Q-factors of resonators with the wider ground-plane spacing of 1.75 mm (not shown here) were lower by about 20 percent than predicted by the theory. The conductor-loss constants calculated here show reasonable agreement with other measurements [5] and predictions [6].

VIII. Conclusions

The losses in coplanar waveguides have been calculated and a normalized conductor loss curve is provided. The quality factors of half-wavelength resonators including radiation effects have been computed and show agreement with measured values.

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Transmission Loss of Thick-Film Microstriplines

SADAYUKI NISHIKI AND SHUOMI YUKI

Abstract —**Thick-film microstripline transmission loss is measured and discussed, and an empirical formula for thick-film microstripline transmission loss is obtained. It is found that the transmission loss of copper thick film is nearly equal to that of thin film for frequencies up to 10 GHz.**

I. Introduction

Thick-film technology is widely applied to mass-produced radio equipment such as citizen-band transceivers, televisions, and radio tuners with good volume production yield. However, in the microwave region, thin-film technology is generally used to fabricate hybrid integrated circuits, because 1) there have been few hybrid integrated circuits to be mass produced in the microwave region, 2) thick-film microstripline has possessed higher transmission loss than that of thin film, and 3) printing and baking methods for making thick-film microstripline have made it difficult to form fine patterns.

However, various conductive thick-film materials have been developed. The composition of thick-film binders has undergone various improvements, and the sheet resistance has been reduced. Ramy has reported that thick film can be utilized like thin film [1].

In our experiment, the microstripline transmission losses of various thick-film materials were measured. As a result of these measurements, an empirical formula for thick-film transmission loss was obtained. In this paper, we would like to discuss our findings concerning thick-film transmission loss.

II. Thick-Film Microstripline

Table I gives the thick-film materials used, and their dc sheet resistance after baking.

The thick-film microstripline was applied with a No. 200 mesh[1] mask onto the alumina ceramic substrate. Fig. 1 shows the thick-film microstripline pattern obtained. Its corners were mitered, as shown in Fig. 1. Its total length was 26 cm and its characteristic impedance was 50 Ω [2]. The same thick film as that for the microstripline was also used for the ground electrode on the opposite side of the substrate. Also, in order to make a comparison with the thick film, an identical thin-film microstripline was produced. A 500-Å thick layer of chromium was evaporated in a vacuum on the alumina substrate, which was followed by a 5000-Å thick layer of gold. It was then electro-plated with 5 μm of gold.

Table II shows the specifications for the alumina ceramic substrate used with the thick and thin films. The thickness of these substrates is 0.635 mm.

The surface roughnesses of the substrate are shown in Fig. 2. The substrate of the thin film is almost flat, while that of the thick film is of a surface roughness of about 2 μm peak to peak. Fig. 3 is a comparison of the profiles of the thick- and thin-film microstriplines measured with a surface tester after baking. The section of the thin film is practically rectangular, while that of the thick film is rounded at the edges, and there is a slight roughness

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[1]No. 200 mesh is formed by 200 40 μm ϕ running vertically and horizontally within a one inch square space.

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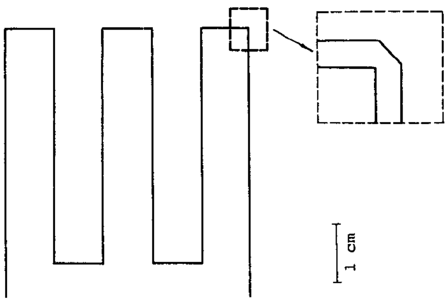


Fig. 1. Formed microstripline.

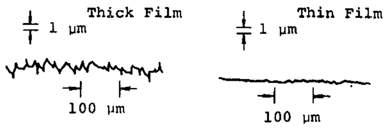


Fig. 2. Surface roughness of substrate.

TABLE I
SHEET RESISTANCE OF THICK-FILM PASTE

Material		Sheet Resistance	
Metal	Bonding Agent*	[mΩ/□]	Measured Thickness [μm]
Au	B1	3.5	8.5
Au	B2	3.0	15
Cu	B3	1.3	25
Cu	B2	1.3	25
Pt/Ag	B1	2.5	18.5
Pd/Au	B3	90	16
Pd/Ag	B2	30	13.5
Pt/Au	B2	70	16.5
Ag	B4	75	25

* B1. Principal component, copper oxide. The bonding to the alumina substrate is due to chemical bonding of alumina and copper oxide.
B2. Principal component, borosilicate glass. Bonding to the alumina substrate is due to mechanical bonding.
B3. Combination of B1 and B2 properties.
B4. Consists of resin. Bonding with alumina substrate is mechanical.

TABLE II
SUBSTRATES USED IN THICK- AND THIN-FILM MEASUREMENTS

Classification	Thick Film Substrate	Thin Film Substrate
Dielectric Constant	9.3	9.6
tanδ	0.0003	0.0001
Alumina Content (%)	96	99.5

over the entire surface. This roughness is about the same as that of the alumina ceramic substrate. Large periodic variations caused by the mesh of the mask can be noticed.

III. EXPERIMENT

Microstripline transmission losses from 200 MHz to 10 GHz were measured for the nine different film materials. The reflection losses for all frequencies were over 10 dB. The ratios of the measured value which was corrected for the reflection loss, to the calculated, are shown in Table III. With one exception, the average of them coincided nearly with 1.6 times the calculated values which do not take into consideration any extra loss due to the dielectric loss or the loss due to the substrate roughness.

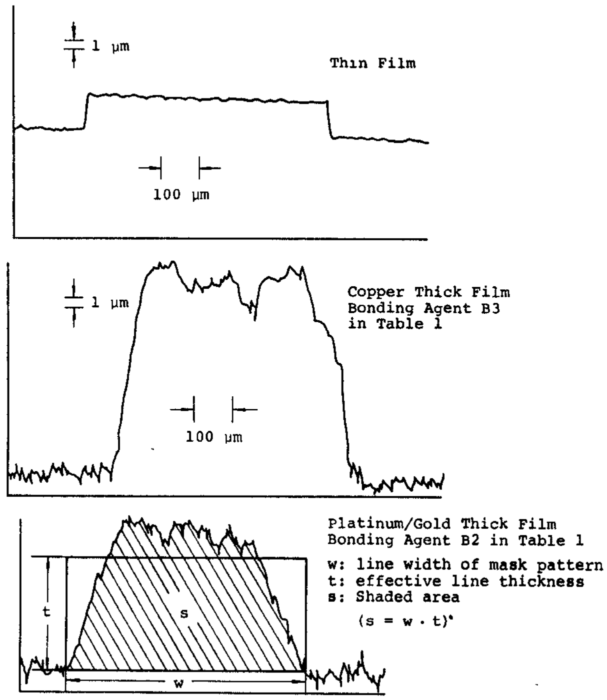


Fig. 3. Stripline film condition.

The calculated values are obtained from the formula for thin-film microstripline conduction loss [3].

When

$$\frac{1}{2\pi} < \frac{W}{H} < 2$$

the conductor loss is obtained from [3]

$$\frac{\alpha_c Z_0 H}{R_s} = \frac{8.68}{2\pi}\left[1-\left(\frac{W'}{4H}\right)^2\right] \times\left\{1+\frac{H}{W'}+\frac{H}{\pi W'}\left[\ln\left(\frac{2H}{t}\right)-\frac{t}{H}\right]\right\} \quad (1)$$

where

- Z_0 characteristic impedance of microstripline,
- R_s conductor sheet resistance,
- t conductor thickness,
- H substrate thickness,
- W actual width of the conductor,
- W' $(=W+t/(\pi K)\cdot\ln(2H/t+1))$ effective width of conductor, taking conductor thickness into consideration, and
- K dielectric constant.

When applying (1) to the thick-film microstripline, W is the line width of the mask pattern. The line thickness (t) is derived from the sectional area of the baked line $W\cdot t$ equal to the sectional area (Fig. 3). The sheet resistance of the thick-film conductor in a dc condition is converted to electrical conductivity. Fig. 4 shows the transmission loss of thick-film microstripline

TABLE III
TRANSMISSION LOSS

Material	Sheet Resistance	Transmission Loss (Ratio of The Measured Value to The Calculated)				
Metal	Bonding * Agent	2 GHz	4 GHz	6 GHz	8 GHz	10 GHz
Au	B1	2.3	2.2	2.3	2.4	2.5
Au	B2	1.6	1.6	1.6	1.6	1.7
Cu	B3	1.4	1.5	1.5	1.6	1.7
Cu	B2	1.4	1.5	1.5	1.5	1.6
Pt/Ag	B1	1.6	1.6	1.7	1.8	1.9
Pd/Au	B3	1.6	1.6	1.6	1.6	1.6
Pd/Ag	B2	1.6	1.6	1.6	1.7	1.7
Pt/Au	B2	1.7	1.7	1.7	1.7	1.7
Ag	B4	1.6	1.6	1.5	1.5	1.6
Thin Film		1.1	1.2	1.2	1.2	1.2

*Refer to the footnote of TABLE I

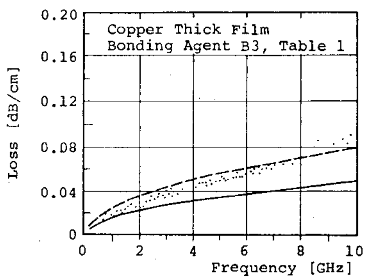
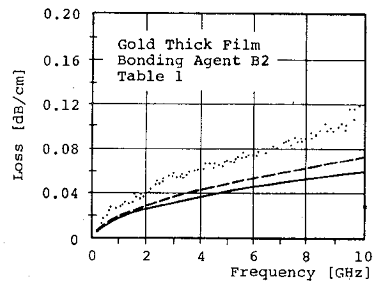


Fig. 4. Transmission loss, copper thick film.



Solid line - Conductor loss only
Dashed line - Loss, taking into consideration conductor loss, dielectric loss, and surface roughness
Dotted line - Actual value

Fig. 5. Transmission loss, gold thick film.

when copper with bonding agents B3 in Table I was used.

The loss is only slightly less than 1.6 times the calculated value.

IV. EVALUATION AND CONCLUSION

Next, we evaluated the transmission loss, using gold thick film, with a borosilicate glass bonding agent, taking into consideration the dielectric loss and surface roughness of the substrate. The dielectric loss was obtained with the following formula [4]:

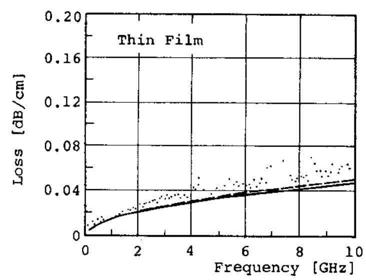
$$\alpha_d = \frac{8.68\pi}{\lambda_g}\left(\frac{qK}{K_e}\right)\tan\delta\,[\mathrm{dB/cm}]$$

$$K_e = 1 + q(K-1) \tag{2}$$

where λ_q is the guide wavelength, q is the filling factor, and K is the dielectric constant.

Also, with regard to the additional amount of loss due to the surface roughness of the substrate, according to Sanderson [5], the surface roughness is assumed to be triangular waves calculated as having a wavelength of 10 μm, and an effective amplitude value of 0.58 μm.

The theoretical value, which takes into consideration the dielectric loss and surface roughness, and the result of the measurement appear in Fig. 5. It can be noted that the measured value is approximately 1.4 times the theoretical value which takes into consideration the dielectric loss and the surface roughness. Fig. 6 shows the theoretical value which includes the dielectric loss and the measured value for thin film. As the substrate for the thin film is almost flat, the excess loss of the roughness is very small. So, we neglected the excess loss of the substrate roughness for thin film. The measured value is 1.2 times the theoretical value for thin film.



Solid line - Conductor loss only
Dashed line - Loss, taking into consideration conductor loss and dielectric loss
Dotted line - Actual value

Fig. 6. Transmission loss, thin film.

We believe that one of the causes of the large deviation in the loss for gold materials, which are chemically bonded, as shown in Fig. 7, is due to the excessive rounding of the edges of the microstripline as compared with the other materials (see Fig. 3).

The ratios of the measured value to the theoretical, which takes dielectric loss and substrate surface roughness into consideration, were 1.4 for thick film and 1.2 for thin film. The difference is believed to be due to the rounding of the microstripline edge, but

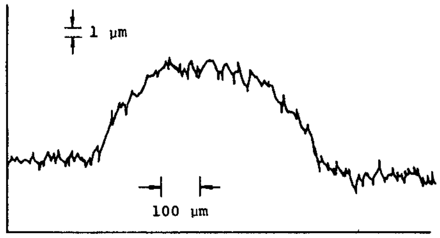


Fig. 7. Film condition of gold thick film utilizing chemical bonding.

it can be noted that thick-film transmission loss is close in value to that of thin film.

This study proves that thick film can be fully utilized up to a frequency of 10 GHz, and it can be concluded that it will be used in low-cost MIC's in mass-produced equipment. Thick film which uses copper (its characteristic impedance is 50 Ω and the substrate thickness is 0.635 mm) has a low transmission loss: 0.005 dB/cm at 0.2 GHz, 0.027 dB/cm at 2 GHz, 0.050 dB/cm at 5 GHz, and 0.087 dB/cm at 10 GHz.

Acknowledgment

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Taking into Account the Edge Condition in the Problem of Diffraction Waves on Step Discontinuity in Plate Waveguide

V. P. LYAPIN, V. S. MIKHALEVSKY, AND G. P. SINYAVSKY

Abstract—A way of improving the convergence of the field-matching method by means of taking into account the edge conditions is proposed. The unknown function, as defined on the matching lines, should be expanded into a infinite set of the orthogonal Gegenbauer polynomials having the required singularity.

One of the ways of improving the convergence of the field-matching method (FMM) being used for solving various problems of electrodynamics is taking into account the edge condition

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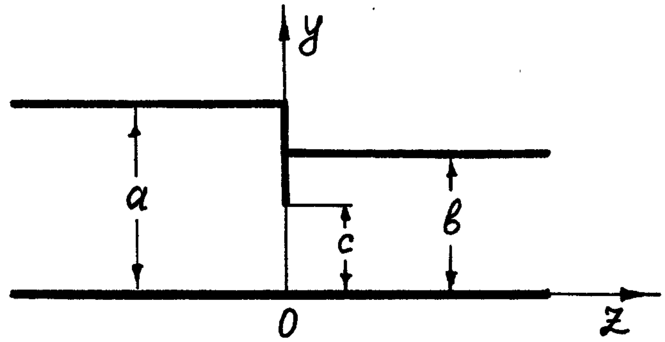

Fig. 1. Step-diaphragm junction in plate waveguide.

in the vicinity of the edge [1], [2]. In the present paper, this technique is applied to the problem of wave diffraction on the step-diaphragm junction in plate waveguides. This is a typical problem to which the calculation of various step discontinuities in rectangular waveguides is reduced.

Unlike the paper [3] where the edge condition is considered as a correction term to the probe function describing the field in the apperture, in this paper the edge condition is taken into account by every term of the expansion.

Let the TM_p-wave with nonzero field components H_x, E_y, E_z be incident from the wide waveguide onto the obstacle (Fig. 1). This particular problem can be reduced to the solution of an integral equation relative to the unknown distribution function $f(y)=(k\gamma_p)^{-1}E_y|_{z=0}$ for a field component in the diaphragm aperture

$$\int_0^c f(y) \sum_{n=0}^{\infty} \left\{ \frac{1}{\gamma_n}\psi_n(y)\psi_n(y') + \frac{1}{\lambda_n}\varphi_n(y)\varphi_n(y') \right\} dy = 2\psi_p(y') \tag{1}$$

where

$$\psi_n(y)=\sqrt{\frac{2-\delta_{0n}}{a}}\cos d_n y \qquad \alpha_n=\frac{n\pi}{a} \qquad \gamma_n^2=k^2-d_n^2$$

$$\varphi_n(y)=\sqrt{\frac{2-\delta_{0n}}{b}}\cos \beta_n y \qquad \beta_n=\frac{n\pi}{b} \qquad \lambda_n^2=k^2-\beta_n^2$$

where δ_{0n} is the Kroneker symbol and $k=2\pi/\lambda$.

The approximate solution of this equation can be found by means of Galerkin's method in the form

$$f(y)=\sum_{i=0}^{N} V_i X_i(y) \tag{2}$$

where

$$X_i(y)=\left[1-(y/c)^2\right]^{-1/2} T_{2i}(y/c)$$

and $T_{2i}(y)$ is the Chebyshev polynomials of the first kind.

With the above chosen basis-function set $X_i(y)$, the boundary condition at $y=0$ is satisfied and the function $f(y)$ possesses the required singular behavior when $y \to c$ [4], the infinite set of $\{X_i\}$ is complete and orthogonal on the interval $[0, c]$. The unknown expansion coefficients V_i can be determined from the system of linear algebraic equations

$$\sum_{i=0}^{N} V_i C_{ik} = R_k, \qquad k=0,1,\cdots,N \tag{3}$$