Optimization of the Thick-and Thin-Film Technologies for Microwave Circuits on Alumina and Fused Silica Substrates

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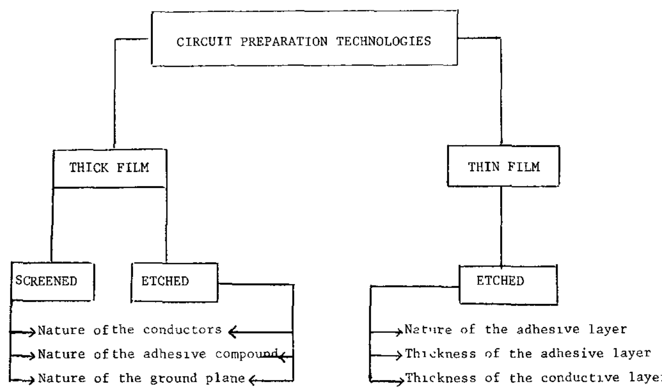
Abstract—**Two technologies can be used in the fabrication of microwave integrated circuits (MIC's), thick film and thin film. This paper describes and compares these technologies. Two types of substrates commonly used in MIC's are tested, alumina (Al_2O_3) for the *X* band, and, because of its better optical flatness and its lower dielectric constant, fused silica (SiO_2) for the *KU* band. The parameters examined are, for thick-film circuits, the nature of metallizations, the method of circuit definition, and the influence of the ground plane, and for thin-film circuits, the influence of the adhesive layer and the thickness of the deposited gold. The parameters selected for the microwave comparison are the microwave Quality factor (*Q*) of the conductors, the adhesion of the conductor, and the ability to be wire bonded. The results show that, when their technology is optimized, thick films can be as good as thin films in the *X* band on alumina substrates. On silica substrates, thin films are better and will be preferred in the *KU* band (by extension of the *C*-band measurements).**

I. Introduction

MICROSTRIP circuits are finding increasing applications at centimeter and even millimeter wavelength because of the ease of integration of components and the compactness and the lower price that their use affords [1]. MIC's, whether passive (couplers, filters, etc.) or active (amplifiers, oscillators, switches, modulators, etc.), are of primary importance in most modern microwave systems.

Since the properties of the materials used in the fabrication of MIC's (metals as well as substrates) are of particular importance [2]–[4], we shall describe first the technologies which can be utilized in the preparation of these types of circuits. Then we shall select the ones which give the best performances in the *X* band with alumina substrates and in the *KU* band (by extension of the *C*-band measurements) with silica substrates. Even though the final conductor thickness may always be considered as thick with respect to the skin effect, we shall use the standard terminology for the two main technologies as summarized below.



II. Experiments

A. Materials

Here we describe the materials that we have used for these experiments: thick-film conductors, thin-film conductors, and substrates.

Thick-film conductors are deposited with the standard process. The ink, which is composed of a powdered metal and an adhesive compound (glass frit or copper oxide) suspended in an organic vehicle, is printed onto a substrate through a screen and then dried and fired at 800–1000° C. We printed these inks through a 200-mesh stainless steel screen using a Microflex printer. We fired in a four-zones belt travel furnace, from BTU Engineering Corporation, with an air flow, except for the inks, from Electro Materials Corporation of America (EMCA), which are fired in a static furnace according to the manufacturer's specifications. For the pattern generation, two techniques have been used. The pattern either is screened directly or etched with a photolitographic process after the substrates have been blanket screened. In this latter case, the gold conductors are etched in an iodine solution composed of iodine and potassium iodine and the copper conductors in an ammonium perfulfate solution com-

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TABLE I
CHARACTERISTICS, MANUFACTURERS, AND PATTERN GENERATION PROCESS OF TESTED INKS

MANUFACTURERS	REFERENCE	METAL	ADHESIVE COMPOUND	RESISTIVITY mΩ/□ *	PATTERN	
					SCREENED	ETCHED
DUPONT DE NEMOURS (DN)	8115	Au	Glass frit	5-10	X	X
	9791	Au	CuO + Glass frit	2-3		X
	9061	AgPd	Glass frit	25-35	X	
	9922	Cu	CuO	1 3		X
ELECTROSCIENCES LABORATOIRES (ESL)	8880	Au	CuO	2-3		X
	8835-1B	Au	CuO + Glass frit	1.8-2.2		X
E M C A (EM)	210	Au	CuO	<2		X
	3264-3	Au	CuO + Glass frit	<2		X
LEP FRANCE (LE)	Expéri-mental	Cu	CuO	1-2		X

*Manufacturer data.

posed of ammonium perfulsate and mercury chloride. The photo etch mask is made with KTFR Kodak photoresist. We have tested also the effects of refiring and of the nature of the ground plane. Table I gives the characteristics and the manufacturers of the tested inks.

For thin-film conductors, we have studied the influence of the composition and thickness of the adhesive layer on the microwave properties of the circuits. Chromium and nickel–chromium were deposited by vacuum evaporation techniques, and iron–nickel–chromium were deposited by vacuum sputtering techniques. After a gold evaporation (300 Å), additional gold is deposited in an electrolytic gold solution manufactured by Engelhard. Although most of the current in a conductor flows in a thin layer, which is the skindepth (δ) as given by the equation

$$\delta = 6.61\sqrt{\frac{\rho}{F \cdot \mu_r \cdot \rho_c}} \tag{1}$$

where ρ is the resistivity of the conductor, ρ_c the resistivity of the copper, μ_r the permeability of the conductor, and F the frequency (in Hz), in practice, the conductor must be thicker than δ.

So we have plated 5, 7.5, and 10 μm of gold to insure a wide margin. The pattern is etched using a photoresist etch mask (KTFR Kodak resin), Au in a iodine solution, Cr and NiCr in an acid cerium solution composed of cerium sulfate and sulfuric acid, and Fe–Ni–Cr in a chlorydric solution composed of chlorydric acid diluted in water.

The substrates used in MIC's should have low dielectric loss (low tgδ) and a very fine surface finish. We have tested the alumina substrates (96 and 99.6 percent) up to the X band and have fused silica for use in the KU band but have tested it in the C band. Table II lists the characteristics of each of them. The thickness is 0.635 mm, and the size is 2.54×2.54 cm.

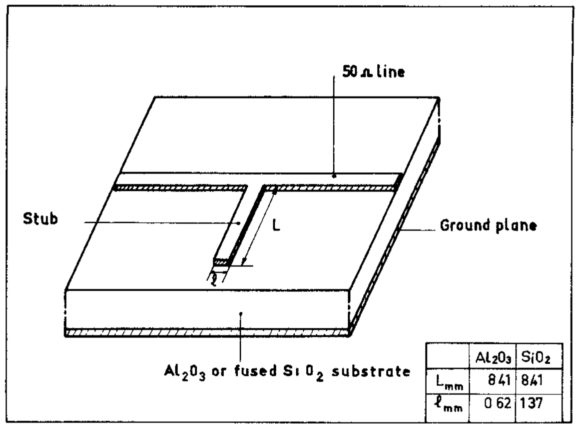

Fig. 1. Pattern selected for the measure of the quality factor.

TABLE II
CHARACTERISTICS OF THE TESTED SUBSTRATES

Substrate	Surface finish (μm) *	Tan δ.10⁴ at 10 GHz *	ε_r Dielectric constant *	Manufacturers
Al_2O_3 96%	20	4-6	≃ 9.2	American Lava
Al_2O_3 99.6%	2-8	2	≃ 9.8	MRC
Fused SiO_2	1	1	≃ 3.8	Quartex

*Manufacturer data.

The transmission loss α dB/cm of a 50-Ω microstripline is the main parameter for microwave use. It is composed of dielectric and ohmic losses. Dielectric losses represent less than 10 percent of total losses due to the low-loss tangent [5]. So we can consider that the attenuation constant α is directly related to the quality of the conductors, which takes into account the electrical and surface finish properties of the substrates and the conductivity and edge definition of the metallic lines.

A very simple circuit configuration has been selected for Q measurement. The pattern is an open stub of $(2K+1)$ $\lambda g/4$ length (at 10 GHz, $K=1$ for Al_2O_3 and $K=0$ for SiO_2) parallel to a 50-Ω line, as shown in Fig. 1. The width of the line and the length of the stub are, respectively, 0.62 mm and 8.41 mm with Al_2O_3 and 1.37 mm and 8.41 mm with SiO_2 substrates. Such a configuration avoids the inaccuracies due to the reproductibility of the coupling slots necessary for the linear $\lambda/2$ or ring resonators which are used generally. Moreover, the measured $Q = F_0/(F_2 - F_1)$ (where F_0 is the frequency at which the attenuation is maximum and F_2 and F_1 are the frequencies where the attenuation is 3 dB lower, see Fig. 2), is related directly to the loss per wavelength $\alpha \cdot \lambda g$. Indeed, the impedance of such a bandstop filter at the center frequency F_0 is

$$Z = R + jX$$

where R and X are the resistive and reactive parts of the impedance. The measured Q is

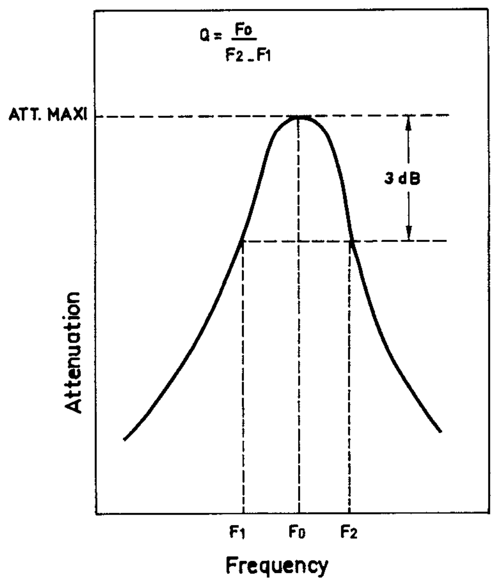

Fig. 2. Definition of the quality factor.

TABLE III
INFLUENCE OF THE ALUMINA PURITY AND OF THE SURFACE FINISH ON Q

INK	PATTERN DEFINITION	Q (10 GHz)	
		Al_2O_3 96% Surface finish : 20 μm	Al_2O_3 99.6% Surface finish : 2 - 8 μm
DN Au 8115	Screened	230	282

$$Q=\frac{X}{R}=\frac{L\omega_0}{R}$$

where L is the inductance of the stub and $\omega_0=2\pi F_0$. Now

$$L\omega_0=\frac{Z_0\cdot\sqrt{\Sigma_{\text{eff}}}}{C}\cdot\omega_0\cdot\frac{(2K+1)}{4}\lambda g_0=\frac{\pi}{2}Z_0(2K+1)$$

where Σ_{eff} is the effective permitivity of the substrate, C the light velocity, Z_0 the characteristic impedance, and λg_0 the guided wavelength at F_0, and

$$R=Z_0\cdot\alpha\cdot\frac{(2K+1)}{4}\lambda g_0.$$

We have

$$Q=\frac{2\pi}{\alpha\cdot\lambda g_0}$$

with α increasing with the square root of the frequency and Q increasing at the same rate. However, the disadvantage of this test structure is to include radiation losses at the open end of the stub. These losses cannot be taken in account precisely, so these measurements are mainly used as comparative results in order to determine the best technological process. All the Q values given in the following tables are mean values derived from at least 5 circuit measurements. The Q dispersion is about ± 5 percent.

In order to test the capability of a semiconductor chip attachment, we have checked the compatibility of the metallizations with epoxy die bonding and with thermocompression and ultrasonic wire bonding. We have utilized a pulsed gold ball bonder from Hughes Cy, a wedge gold bonder from Kulicke and Soffa Cy, and an ultrasonic gold and aluminium wire bonder from Precimeca.

TABLE IV
INFLUENCE OF THE GROUND PLANE ON Q

Ink on Al_2O_3 99.6%	Pattern definition	Nature of ground plane	Q (10 GHz)	Case
ESL Au 8880	Screened then etched	ESL Au 8880	419	A
DN Ag Pd 9061	Screened	DN Ag Pd 9061	69	B
ESL Au 8880	Screened then etched	DN Ag Pd 9061	354	C

TABLE V
INFLUENCE OF THE PATTERN DEFINITION ON Q

INK on Al_2O_3 99.6 %	ADHESIVE COMPOUND	Q (10 GHz)	
		SCREENED LINES	ETCHED LINES
ESL Au 8880	Copper oxide	319	419
DN Au 8115	Glass frit	282	385

TABLE VI
INFLUENCE OF FIRING CONDITIONS ON Q

INK on Al_2O_3 99.6%	Pattern definition	Adhesive Compound	Q(10GHz) One firing 850°C	Q(10GHz) Two firing at 850°C	Q(10 GHz) One firing at 930°C and then one at 850°C
DN Au 8115	Screened	Glass frit	267	282	/
ESL Au 8835-1B	Etched	Glass frit + CuO	/	367	404

III. RESULTS AND DISCUSSION

A. Alumina Substrates in X Band

Table III compares alumina substrates of different purities. As one can see, the microwave losses are about 20 percent higher with the 96-percent Al_2O_3 substrates. This result can be explained by differences in the surface finish, tan δ and Σr (Table II), and the included impurities.

Although it is well known that silver–palladium inks, such as DN AGPD 9061, are worse than gold inks for microwave use (see comparison A-B in Table IV), it can be of interest to use such an ink for the ground plane in order to lower manufacturing cost. However (see comparison A-C in Table IV), this solution seriously reduces the Q of the circuit, even if the transmission line is made with a high-performance ink such as ESL Au 8880.

Table V shows that etching the thick film considerably improves (by about 30 percent) the MIC's performances as compared to direct screening, independent of the adhesive compound used. This is certainly due to the better edge and line width definition of the etched lines (see Figs. 3 and 4), since maximum current density is at the edges of the microstripline [5].

Table VI gives some effects on Q of different firing conditions of the thick films. It seems that two successive

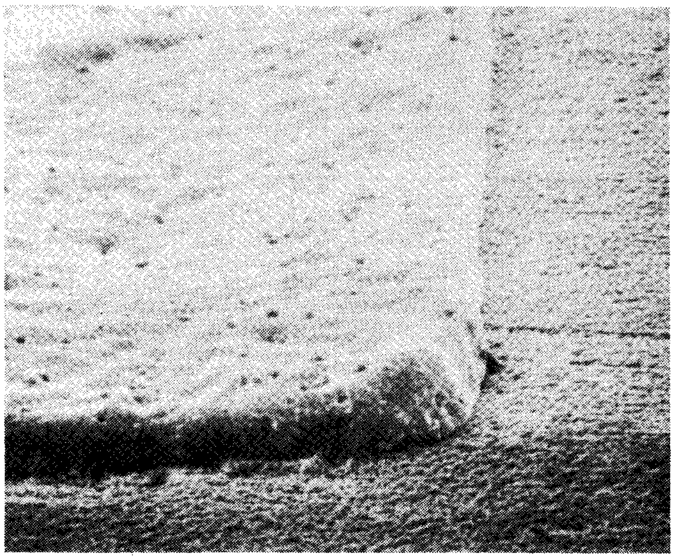

Fig. 3. Profile of an etched line.

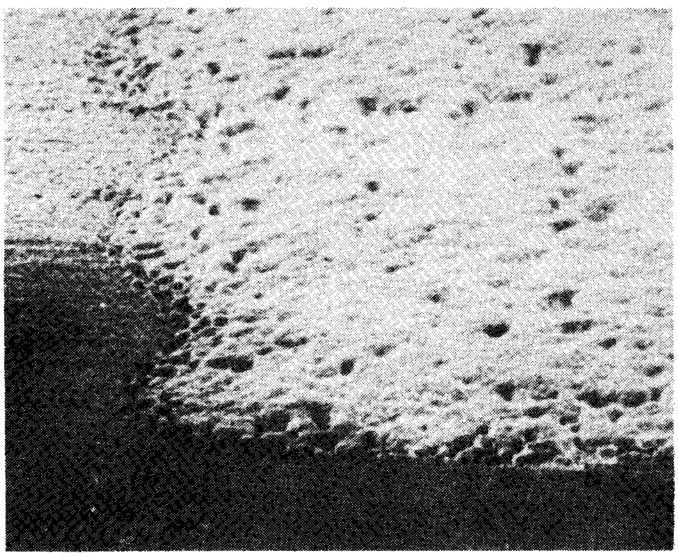

Fig. 4. Profile of a screened line.

firings improve the MIC's performance. This is in good agreement with the results obtained in other laboratories [6], [7].

Thick-film conductors are bonded to alumina substrates in three different ways [8]. The first is called reactive bonding. A base metal (generally copper) is alloyed with the powder metal. When fired, the base metal oxidizes at the surface, and this oxide chemically attacks the substrates and forms a strong bond. The second is called glass bonding, in which a finely divided glass is mixed with precious metal powders. During the firing, the glass softens and penetrates voids in the metal layer and grain boundary regions in the substrate, ensuring the formation of a bond. The third, called mixed bonding, is a combination of the two previous methods. In Table VII, we can see that the best results are obtained with the reactive-bonding inks. For thin film two different adhesive layers were tested, and it seems that, even taking into account

TABLE VII
INFLUENCE OF THE ADHESIVE LAYER ON Q

Film technology on Al_2O_3 99.6 %	Adhesive Compound	Conductive layer (etched)	Q 10 GHz
Thick film	Copper oxide	ESL Au 8880	419
		EM Au 210	417
	Copper oxide + glass frit	ESL Au 8835-1B	404
		EM Au 3264-3	384
		DN Au 9791	380
	Glass frit	DN Au 8115	385
Thin film	100 Å Cr	Gold (10 µm)	436
	50 Å Fe-Ni-Cr	Gold (10 µm)	411

TABLE VIII
INFLUENCE OF THE CONDUCTOR THICKNESS ON Q

Thinfilm origin; on Al_2O_3 99.6 %	Adhesive Compound	Gold thickness (µm)	Q 10 GHz
MRC	100 Å Cr	10	436
CNET	100 Å Cr	7.5	420
MRC	100 Å Cr	5	300

TABLE IX
RESISTIVITY OF DIFFERENT GOLD ELECTROPLATING LAYERS, MEASURED BY THE FOUR PROBES RESISTIVITY MEASUREMENT

Thickness µm	Sheet resistivity mΩ/□	Resistivity : ρ µΩ cm
5	5.98	2.99
10	2.49	2.49

the Q measurement accuracy of ± 5 percent, chromium as an adhesive layer is slightly better than Fe–Ni–Cr.

The influence of the conductor thickness d has been studied in the case of thin-film circuits with electrodeposited gold varying in thickness (between 5, 7.5, and 10 μm). The skin depth δ for a gold conductor at 10 GHz is theoretically 0.8 μm, as shown in (1). The thickness of the conductor, theoretically, is assumed to be three times ($d/\delta = 3$) the skin depth [9]. We found that a ratio d/δ of approximately 10 (see Table VIII) was required to minimize the losses.

As we can see in Table IX, this surprising result can be partly explained by differences in the resistivity values of the electroplated gold versus the thickness. It is necessary to thicken it to 10 μm in order to get a resistivity approaching that of the bulk resistivity of gold (2.44 $\mu\Omega \cdot$cm). The relatively high resistivity of the 5-μm layer is probably due to the porosity of the electroplated layer.

Qualitatively, all the metallizations give good bonding results for epoxy die bonding and for aluminum ultrasonic wire bonding. For gold thermocompression ball bonding and wedge bonding, the copper metallizations do not give as good bonding results as the DN Au 8115-thick film. This is probably due to the high concentration of glass frit in the ink, since etching with an HF solution considerably improves the results without degrading the MIC performance. For gold ultrasonic wire bonding, only the ESL Au 8880 ink gives good results.

TABLE X
COMPARISON, FOR MIC PERFORMANCE, OF THICK FILMS AND THIN FILMS ON 99.6-PERCENT Al_2O_3 SUBSTRATES

Film technology	Pattern definition	Ink's reference	Adhesive Compound	Thickness and nature or conductive layer	Q 10 GHz
Thin film	Etched	MRC	100 A Cr	10 µm gold	436
	"	CNET	"	7.5 µm gold	420
	"	MRC	"	5 µm gold	300
	"	CNET	50 A FeNiCr	10 µm gold	411
Thick film	Etched	ESL 8880	Copper oxide	15 µm gold	419
	"	EM 210	"	" " "	417
	"	DN 9922	"	21 µm copper	455
	"	LE exp.	"	27 µm copper	432
	"	DN 8115	Glass frit	12 µm gold	385
	"	DN 9791	Copper oxide + glass frit	13 µm gold	380
	"	EM 3264-3	"	15 µm gold	384
	"	ESL 8835-1B	"	12 µm gold	404
	Screened	DN 8115	Glass frit	12 µm gold	282
		DN 9061	"	10 µm Ag Pd	69

Table X summarizes the MIC performances of the different thick- and thin-film technologies on 99.6-percent alumina substrates. It can be deduced that with a proper choice of materials, thick etched films give as good results as thin films up to the *X* band, and that they can be used in the production of MIC's. The inks have to be screened and then etched; their adhesive compound should be a copper oxide; their conductive layer should be copper or gold; the firing conditions should be optimized. The best manufactured inks are ESL Au 8880, EM Au 210, and DN Cu 9922. The best metallization is provided by the DN Cu 9922 copper thick-film ink.

The importance of etching thick films in order to achieve a quality comparable to thin films has been pointed out. Even if the process cost is higher when thick films are photoresist etched, it remains easier than vacuum metallization, and it is compatible with the use of the other thick-film components such as resistors and capacitors [10]. However, this technology is limited to line width definitions of 40 μm; when fine line definition is requested, for example, 3-dB Lange couplers or coupled line filter structures, the use of the thin-film technology becomes necessary.

B. Fused Silica Substrates for Use in KU Band

For use up to the *KU* band, fused silica substrates are preferred to alumina substrates because of the better optical flatness of the surface finish (which is free from inclusions or pits which are frequently found in alumina), and the lower dielectric constant ($\Sigma r = 3.8$ for fused SiO_2, 9–10 for Al_2O_3). The lower dielectric constant should permit the fabrication of MIC's with lower microwave losses and greater line size. However, its low thermal conductivity makes it inappropriate for the direct attachment of active semiconductor devices with high power dissipation.

In order to arrive at some comparisons for the different technologies available in our laboratory, preliminary *Q* measurements have been made at 5 GHz and are extrapolated to the *KU* band. Direct measurements at 15 GHz have not yet been achieved because of parasitic resonance effects. New circuits are being made which will permit *KU*-band measurements.

TABLE XI
THICK-FILM MICROWAVE LOSSES ON FUSED SILICA SUBSTRATES

Thick film ink (etched)	Adhesive layer	Q(5GHz)
Gold ESL Au 8880	Copper oxide	364
Gold DN Au 8115	Glass frit	325
Gold DN Au 9791	Copper oxide + glass frit	342
Copper L.E. Exp.	Copper oxide	361

TABLE XII
COEFFICIENT OF LINEAR EXPANSION OF MATERIALS

Element	Al_2O_3 99.6%	Al_2O_3 96%	Fused SiO_2	Gold	Chromium
Coefficient of linear expansion at 25°C	6.6 10^{-6} °C^{-1}	6.4 10^{-6}.°C^{-1}	0.4 10^{-6}.°C^{-1}	14 2 10^{-6}.°C^{-1}	6 10^{-6} °C^{-1}

There is no problem in etching gold and copper thick-film inks on fused silica substrates, but, after the etching, the surface is rough, and we have noted that the adhesion is much stronger than on alumina. On these substrates, as we can see in Table XI, gold thick-film inks with copper oxide as an adhesive layer are better than the thick-film inks with glass frit as an adhesive layer. On the other hand, gold and copper thick-film inks have similar losses.

The greatest problem in the realization of thin films on fused silica substrates is the adhesion after the electrodeposition of about 7–10 μm of gold, particularly at the time of the test of the gold thermocompression wedge bonding where the small lines lift off with a fracture of the substrates (as observed by E. J. Crescenzi [11]). This is not a problem with alumina substrates. These fractures are due to the thermal shock which puts the gold thin film and the adhesive layer under an excessively high stress which is due to the large difference between the thermal expansion coefficients of the metallization and the fused silica; this difference, however, is insignificant in the case of alumina substrates (see Table XII). Diffusion of the adhesive layer metal, such as the chromium in SiO_2, also can occur during stress relief at elevated temperatures [12], thus reducing the adhesion. We have improved the adhesion by employing a low-stress deposition process. Just before evaporation, the substrates are heated under vacuum to 300°C; then the metal layer is evaporated on the hot substrates at 250°C. On the other hand, the damaging effects of thermocompression wedge bonding can be avoided by employing a pulsed thermocompression ball bonder in which only the wire is heated for a very brief time.

The influence of the nature and thickness of the adhesive layer for thin films on microwave losses is given in Table XIII. To interpret these results, two effects have to be taken into account:

1) *Q* decreases when the adhesive layer is thicker. This is supposed to be due to the underetching effect (when the pattern is etched, the chemical attack introduces a nonho-

TABLE XIII
INFLUENCE OF THE NATURE AND THICKNESS OF THE ADHESIVE LAYER ON THIN-FILM MICROWAVE LOSSES

ADHESIVE LAYER		CONDUCTIVE LAYER	Q (5 GHz)
Nature	Thickness ± 20 Å		
NiCr	100 Å	7μm of gold	477
"	200 Å	"	425
"	250 Å	"	352
Cr	100 Å	"	477
"	200 Å	"	451

TABLE XIV
MICROWAVE LOSSES ON ALUMINA AND FUSED SILICA SUBSTRATES AT 5 GHz

SUBSTRATE	FILM TECHNOLOGY	CONDUCTIVE LAYER	ADHESIVE LAYER	Q (5 GHz)
Al_2O_3 99.6%	THIN FILM	10 μAu	100 Å Cr	280
	THICK FILM	ESL Au 8880	Copper oxide	270
		DN Au 8115	Glass frit	240
		DN Cu 9922	Copper oxide	290
SiO_2	THIN FILM	7 μAu	100 Å Cr	477
	THICK FILM	ESL Au 8880	Copper oxide	364
		DN Au 8115	Glass frit	325
		DN Cu 9922	Copper oxide	361

mogeneity in the cross section of the line) which occurs in the area of maximum current density and which becomes very important as the thickness increases.

2) The difference between the Cr and NiCr adhesive layers are supposed to be due to the degree of oxidation of these layers. For a thickness of 100 Å, one can suppose that both layers are completely oxidized, and that the Q's are similar. For thicker layers, Cr and NiCr are not completely oxidized, but Cr, having a lower resistance than NiCr, has a better quality factor.

In order to compare the relative quality of the thick-film and thin-film metallization processes on SiO_2 and Al_2O_3 substrates, we have measured the quality factor at 5 GHz in each case. The results are listed in Table XIV. On alumina substrates, the results confirm those obtained at 10 GHz with a measured ratio $Q(10\text{ GHz})/Q(5\text{ GHz}) \cong 1.55$, i.e., very near from the square root of the frequencies ratio. With SiO_2 substrates, however, thin films are much better than thick films regardless of whatever thick-film process is used.

To interpret these differences, we have assumed that gold or copper diffusion into SiO_2 substrate occurs during the firing of thick-film inks at 800–1000°C. This explanation seems to be confirmed by the following experiments. Two lots of circuits were prepared, one with the classical gold thick-film technology and the other where the fused silica (before screening, firing, and etching) was coated with an Fe–Ni–Cr thin-film layer in order to prevent the supposed migration. In this latter case, after the conductive layer etching, the oxidized layer of Fe–Ni–Cr may either be etched or not. The results of Table XV show that

TABLE XV
EFFECT OF GOLD MIGRATION INTO FUSED SILICA SUBSTRATES ON Q

Ink	Under layer of 100 Å : Fe Ni Cr	Under layer etched	Q (5 GHz)
ESL Au 8880	no	-	364
ESL Au 8880	yes	no	452
ESL Au 8880	yes	yes	424

the quality factor Q is improved by about 25 percent by the use of a Fe–Ni–Cr layer and becomes nearly as good as thin film. The quality factor is lower when the Fe–Ni–Cr oxidized layer is etched undoubtedly because of underetching.

Although these conclusions derive from 5-GHz measurements, we can assume that they remain qualitatively valid up to the KU band. Otherwise, the comparison of Q for silica and alumina substrates metallized with chromium gold thin films (see Table XIV) can be made at 5 GHz. The measured ratio is

$$\frac{Q(SiO_2)}{Q(Al_2O_3)} \cong 1.70.$$

The theoretical ratio deduced from Pucel *et al.* [5] is

$$\frac{Q(SiO_2)}{Q(Al_2O_3)} = \frac{\alpha(Al_2O_3)}{\alpha(SiO_2)} \cdot \sqrt{\frac{\Sigma_{\text{eff}}(SiO_2)}{\Sigma_{\text{eff}}(Al_2O_3)}}$$

$$= \frac{4.6K}{2.5K} \cdot \sqrt{\frac{2.98}{6.60}} \cong 1.24$$

where K depends on impedance and frequency.

This difference between the theoretical and measured quality factor ratios may be attributed not only to the different radiation losses of the open stub but also to the different surface finishes between alumina and silica [4], as shown in Table II. Indeed, the values of attenuation/cm derived from these Q measurements at 5 GHz are with alumina, $\alpha = (2\pi)/(Q\lambda g_0) = 0.11$ dB/cm, whereas the theoretical value is 0.038 dB/cm [5], and with silica, $\alpha = 0.043$ dB/cm, whereas the theoretical value is 0.021 dB/cm, [5].

IV. CONCLUSIONS

This study was carried out to determine the best technology for microstriplines at X and KU bands. The conclusions are summarized as follows. 1) At the X band with 99.6-percent alumina substrates, thick films give results as good as thin films. However, the inks must have copper oxide as an adhesive compound and gold or copper as the metal powder. They must first be screened and then etched to the desired pattern. 2) With the fused silica substrates, the thin films give the best performances. However, they must not be subjected to thermal shock which will degrade their adherence. 3) High quality substrate surface finishes are required in order to minimize losses.

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A Generalized Spectral Domain Analysis for Coupled Suspended Microstriplines With Tuning Septums

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***Abstract*—An efficient computation method is developed for solving the microstrip-type structures in which a number of conducting strips are located on several interfaces of dielectric layers. The method is applied to the coupled suspended microstripline with tuning septums on the underside of the suspending dielectric layer. The numerical solutions obtained by the new method are compared with available data. The method is believed useful in the design of tightly coupled structures such as the 3-dB hybrid as well as of transitions between different transmission lines for microwave and millimeter-wave integrated circuit application.**

I. INTRODUCTION

THIS PAPER describes a new efficient method for computing characteristic impedances and effective dielectric constants of the even and odd modes in the coupled suspended microstriplines with grounded tuning septums. The cross section of the structure is shown in Fig. 1. This structure recently has been introduced by Aikawa [1], [2] to circumvent some of the practical difficulties in realizing coupled microstripline structures such as a 3-dB hybrid.

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It is well known that the phase velocities or the effective dielectric constants of the even and odd modes must be identical or close to each other within a few percent in order that the coupled microstripline structure can be used as a directional coupler. In addition, the separation $2S$ between two strips must be reasonably large so that the structure can be fabricated without undue practical difficulty. Several methods have been reported to control the phase velocities of the even and odd modes and to realize a tightly coupled structure. They include the dielectric overlay [3], the wiggly line [4], and the interdigitate line [5].

In the method proposed by Aikàwa [2], the value of $2S$ to obtain a tight coupling is relatively large, and the phase velocity of the even mode can be tuned by changing the width of the grounded septums. It is also pointed out that the proposed structure is potentially useful as a reverse phase hybrid ring [1]. We also believe this structure is useful at millimeter-wave frequencies because it is a modification of the suspended microstripline [6].

The analysis of the structure has been done by the use of the successive over-relaxation technique [1], [2]. In this paper, an alternative and very efficient numerical technique is developed for analyzing the structure shown in

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