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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

SOME PRACTICAL CONSIDERATIONS
FOR REDUCING THE SURFACE RESISTIVITY
OF X-BAND COMPONENTS

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Group 46

TECHNICAL NOTE 1965-41

11 AUGUST 1965

REVISED 13 JUNE 1966

Best Available Copy

LEXINGTON

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ABSTRACT

In a recent experimental study program involving X-band waveguide components, various factors affecting RF resistivity were investigated. Specific results of this investigation included: 1) the successful reduction of the RF resistivity of conventional beryllium copper castings by electroplating with higher conductivity metals, 2) decreasing RF resistivity by lowering surface roughness, 3) the attainment of microwave components cast from a higher conductivity casting alloy than beryllium copper, 4) lowering of the RF resistivity by minimizing the effects of surface oxides and sub-surface contaminants, 5) the use of OFHC and electroformed copper components to achieve low RF resistivity, and 6) an evaluation and comparison of dielectric and metallic protective coatings which inhibit the deterioration of waveguide surfaces.

Accepted for the Air Force
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SOME PRACTICAL CONSIDERATIONS FOR REDUCING
THE SURFACE RESISTIVITY OF X-BAND COMPONENTS

INTRODUCTION

In certain areas such as low-noise receivers and high-power radar systems, low-loss waveguide components are becoming more important every day. Problems incurred with the constant improvement of the noise temperature of these receivers and the control of excessive heating in the high-power systems are causing a new look to be taken at waveguide components made from low-loss materials and the problems associated with minimizing waveguide ohmic losses are even more severe when one works at millimeter wavelengths.

The purpose of this paper is to provide a practical guide to the engineer who is involved with low-loss microwave requirements. To that extent methods of reducing the RF surface resistivity of microwave components will be considered and treatments will be described that can be used to inhibit the oxidation and contamination of waveguide components.

The first area to be investigated was the use of high-conductivity electroplated coatings and various electroplating techniques to reduce the RF resistivity of conventional beryllium copper magic tee castings. To the author's knowledge, no such work has been reported in the literature on this subject. While Allison and Benson⁽¹⁾ and Benson⁽²⁾ considered silver and copper electroplating, they only used samples of precision-drawn waveguide tubing as the substrate in their experiments, and in (1) they calculated the RF resistivity exclusively from a mathematical expression which took into account surface roughness. Later Benson⁽²⁾ completed a measurement of the RF resistivity of electroplated precision-drawn tubing using a standing-wave technique in conjunction with long waveguide samples.

In the study presented now, measurements of the RF resistivity were obtained from a three-section resonant cavity Q meter utilizing a technique similar to that employed by Maxwell⁽³⁾ at K-band. The problems of obtaining a highly conductive electroplated coating are considerably more complex for a cast surface than for a precision-drawn surface. Factors such as high porosity and considerable surface roughness, which are common to castings, do not provide a suitable base for an electroplated coating. However, certain careful, pre-electroplating techniques which were used in this study can greatly improve the quality and conductiveness of the final electro-deposited coating.

Much work already exists in the literature on the subject of surface roughness vs. attenuation.⁽¹⁻¹⁰⁾ However, it appears that no program has been reported which actually measured the change in RF resistivity that one obtains when different techniques are used to smooth the internal surface roughness of various microwave castings. This study undertook those considerations and concentrated on the effective employment of new smoothing procedures which utilized chemical and abrasive techniques.

The need itself for electroplating and its associated problems can be diminished sharply. A practical casting alloy with an extremely high conductivity has been found which can replace the poorly conductive conventional beryllium copper alloy. Work with commercial casting houses was carried out successfully in this endeavor and high-conductivity cast components were obtained and tested. Peculiarly enough, no references were found in the literature concerning measurements of the RF resistivity of these known alloys.

Other important areas which received attention included the cleaning and removal of contaminants and oxide coatings from the surfaces of various waveguide materials, and a study of electroformed copper components and how various changes in plating chemistry affect the RF resistivity.

The ability to protect waveguide surfaces with a coating which will not affect the RF performance of the system is of paramount importance. The RF surface resistivities of many metallic and dielectric coatings were measured and the effect of aging was noted in many cases. Four coatings, two metallic and two dielectric, proved to be very effective in limiting the degradation of waveguide surfaces. Except for some early work by Maxwell⁽³⁾ at K-band, which only included palladium and rhodium, almost no information has been published

concerning the RF surface resistivity of metallic protective coatings.*

Normalized RF Surface Resistivity

A quantity ideally suited to represent the relative performance of the experimental alloys and surface materials used in this study is a normalized surface resistivity, r_s . This parameter is defined as the ratio of the measured value of the surface resistivity of the material under question to the handbook value** of the surface resistivity of pure copper, at the same frequency and with an ideally flat surface. Thus the need for an accurate measurement of the DC conductivity[†] is eliminated. The measured value of the RF surface resistivity was obtained by measuring the unloaded Q of a three-section resonant cavity whose middle section was fabricated from the material under investigation. The end pieces of the cavity consisted of an iris and short circuit designed to produce a current null at the flange connections to the middle waveguide section. The unloaded Q and other parameters of this cavity necessary to determine the unknown surface resistivity were measured on an X-band Q meter. The Q meter was operated for the most part at 7.57 GHz.

* Beck and Dawson⁽⁴⁾ have provided some interesting information about a few selected lacquered coatings at X-band frequencies.

** The handbook value of the RF surface resistivity of pure copper which was used throughout this work to generate the normalized RF surface resistivity was evaluated from the following expression:⁽¹¹⁾ $R_s = 2.61 \times 10^{-7} \sqrt{f}$ ohms. Since this expression is based on a previous measurement of the DC conductivity of a copper sample, it is therefore possible to obtain normalized RF surface resistivities which will measure less than unity.

[†] A source of error in measuring a non-normalized surface resistivity, as pointed out by Benson,⁽⁵⁾ is the error in assuming that the handbook value of the DC conductivity is correct for the material used.

The operation and construction of this Q meter is described in Appendix I. Appendix II contains a derivation of the expression used to calculate the unknown surface resistivity from the data taken with the Q meter, and an error analysis of this technique appears in Appendix III.

I A C S

Another relative quantity which is used today primarily in the metal industry to define conductivity is the "percent IACS". The International Ann-ealed Copper Standard uses the value of the conductivity of copper to represent 100 percent IACS. Since this is a volumetric measurement performed essentially at DC, it cannot be used to accurately estimate the RF surface resistivity of a material. However, when the RF surface resistivity is already known, then corresponding percent IACS may be very useful as a comparison, keeping in mind, however, that it must be considered to have an ideally flat surface. The percent IACS can be calculated very simply when the normalized RF surface resistivity, r_s , is known:

$$\text{percent IACS} = \left(\frac{1}{r_s}\right)^2 \times 100 \quad . \quad (1)$$

I. BERYLLIUM COPPER CASTINGS

A large number of components which are commonly used today in microwave assemblies can only be produced economically by employing casting techniques. Practically all the components in the smaller waveguide sizes are cast from an alloy of beryllium and copper. The effect that these beryllium copper components have on the noise temperature of low-noise receiver systems is quite dramatic. As an example of this, take the case of an X-band radar which can transmit a 100-kilowatts CW and receive simultaneously on different frequencies. If there are ten feet of OFHC copper waveguide between the antenna and the receiver, what is the increase in effective noise temperature when three feet of the OFHC copper are replaced by beryllium copper components? Because of the high transmitter power level, the waveguide common to both the transmitter and

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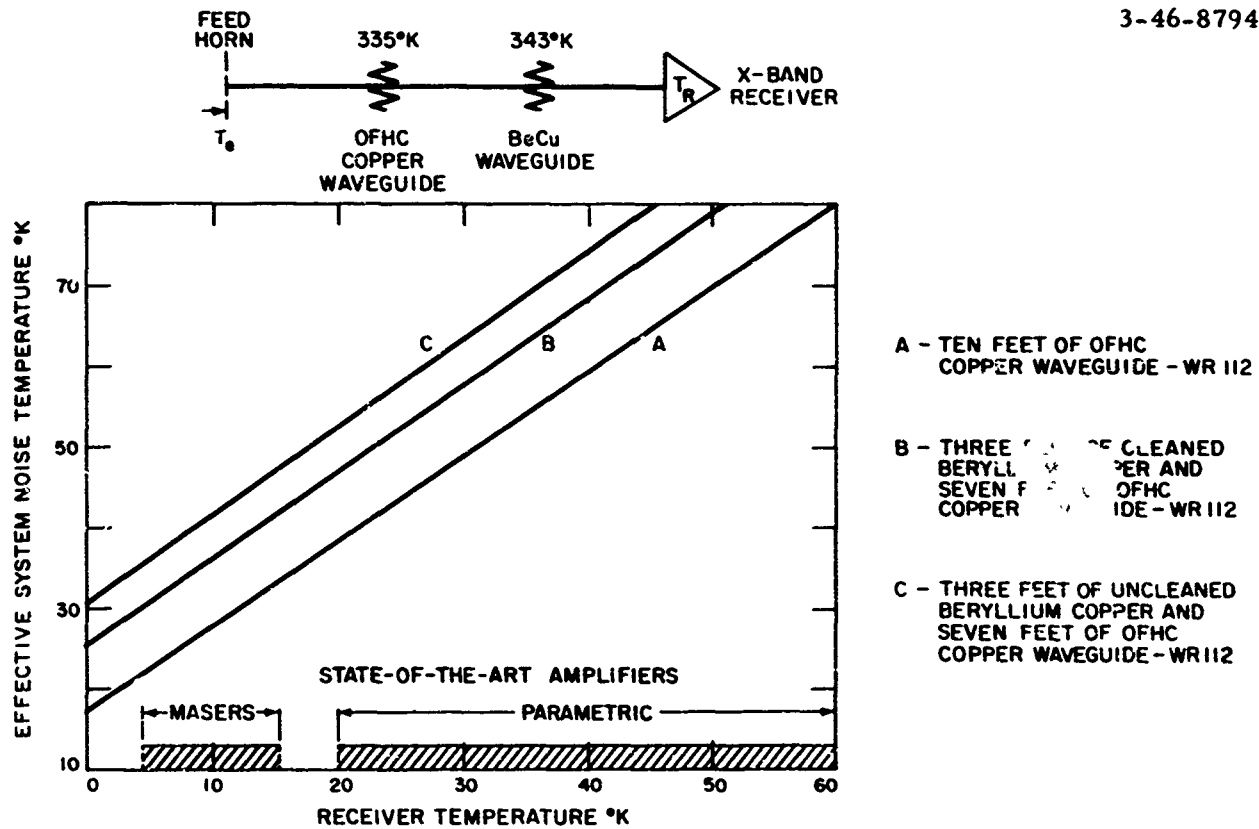


Fig. 1 Effect of waveguide losses on noise temperature at X-band.

receiver lines will have to be cooled. Typical cooled temperatures which might be encountered are 335°K for the OFHC and 343°K for the beryllium copper. Although these water temperatures may seem high, without providing this cooling the waveguide would be expected to melt. Figure 1 shows what effective system noise temperatures can be expected at the antenna feed in both cases for various receiver temperatures. The antenna temperature itself is not included in these numbers. It is seen from the figure that the substitution of three feet of beryllium copper causes an increase in the system noise temperature of approximately 14°K . While 14°K might be negligible in systems with higher noise temperatures, it becomes intolerable to those people striving to obtain low-noise systems.

Foundry Techniques

The following background material may be helpful in understanding some of the methods presently being used in the foundry industry. There are two major techniques which apply to the casting of microwave components--the more traditional "investment" casting process and a recent derivative called "shell-mold" casting. In investment casting, a wax impression of the component to be made is hardened in a metal die. The wax shape is then dipped into a slurry of resin-bonded sand and baked until hard. At the same time the wax investment is lost by melting, giving rise to its other name, the "lost-wax" process. The mold is then ready for the casting alloy. Shell-mold casting eliminates the wax investment and the sand core is simultaneously shaped and hardened directly from heated machined dies.

The process by which castings cool is referred to as "zone cooling." The mechanics of this cooling process often cause impurities in the alloy to rise to the surface. After the casting has cooled, the sand core is usually cracked away by a blast of fine sand. As a final finishing step, the castings are further blasted with small glass beads, and then cleaned in a solution of caustic soda; this commonly results in a surface finish of about 100-150 microinches.* If the caustic soda is not completely removed, problems may arise at a later time

* Sometimes it is possible for casting houses to lower the surface roughness to 60-70 microinches.

if the castings are ever acid cleaned, as they would be if an electroplated coating were to be applied. The acid reacts with the remaining caustic soda to form corrosive salts, which will undermine any coating and cause peeling at some later date.

The RF surface resistivity of such beryllium copper castings in their "as-delivered" condition, which means they have not been acid etched, has been measured to be about 3.3 times greater than that of unalloyed, pure copper. Since the average power loss is proportional to the surface resistivity, the loss encountered with beryllium copper castings is often more than three times greater than that of components fabricated from OFHC copper. This RF resistivity corresponds to about 9.2 percent IACS for an ideally flat surface of the same material. Eddy current measurements^{*} at 60 KHz on beryllium copper castings indicate a conductivity of only 17-19 percent IACS.

Electroplating Castings

There are many ways in which the high resistivity of beryllium copper castings can be lowered. Prolonged etching of the internal surfaces with a strong reagent, such as nitric acid, is a method which removes the top layer of a casting where most of the impurities are found. This exposes a more pure and conductive layer beneath. When a beryllium copper sample was placed in a commercially prepared nitric acid, which contained special polishing additives, for 15 minutes, the normalized RF surface resistivity decreased from 3.3 to 2.5. (Hereafter, I will refer to this acid as acid "A".) However, this method has obvious drawbacks since the acid changed the internal dimensions of the waveguide by 2-3 thousandths of an inch during the 15-minute period.

Another method of lowering the ohmic losses inherent in beryllium copper castings is not to use them at all and change to a different casting alloy which has a higher conductivity. (Casting alloys other than beryllium copper will be discussed in the next section.) However, many microwave components presently are cast in beryllium copper and therefore electroplating techniques using high-conductivity metals, such as silver and copper, are both necessary and practical.

Electroplating beryllium copper castings definitely improves the conductivity of the component, but it seems that the full potential of the high-conductivity coatings cannot be realized. The prime reason for this seems to

* Using a Magnatest Model FM-110 conductivity meter, manufactured for Magnaflux Corporation by Institute Dr. Förster, Germany.

be the surface roughness of the casting itself.⁽⁵⁾ Electroplating a casting without first reducing its surface roughness may have little or no effect on the surface resistance if the initial roughness corresponds to more than a skin depth. In fact, electroplating over a cast surface may often produce a surface that is even rougher than the original one. Any reduction of the resistivity due to the higher conductivity of the plating material may be lost, or at least reduced, by the increase in the RF current paths that is caused by the roughness of the surface. In some excellent photomicrographs, Allison and Beuson⁽¹⁾ have shown how a silver-plated surface can be much rougher than the original surface. Benson,⁽²⁾ von Baeyer⁽⁸⁾ and Lending⁽⁷⁾ all have reported that silver-plated surfaces may not enhance conductivity at all* because of its peculiarity of faithfully following all the irregularities of the base surface and sometimes adding to it. Electroplated copper, on the other hand, seems much better in this respect since it tends to have greater leveling and smoothing properties than the electroplated silver.

In the experiments carried out here, beryllium copper, folded H-plane magic tees were electroplated with both copper and silver. Various electroplating procedures and techniques were tried and the results can be seen in Table I. It seems that the best coating results when: 1) the casting is burnished or smoothed internally so that the surface roughness is reduced to a skin depth or less; 2) the electroplating current is periodically reversed, tending to deposit a level surface; and 3) internal electrodes are used to build up a thick coating on the inside of the component, especially around the inside corners. An interesting variation of the smoothing process which preceded the electroplating was tried with some degree of success on the silver-plated magic tee, No. 523. This consisted of depositing multiple layers of the silver, three to be exact, with an extensive burnishing of the internal waveguide surfaces between each coating. The result was a considerable improvement over the previous magic tee castings which were electroplated with silver (see Table I).

It was also discovered that when the magic tees were copper plated in a rochelle salt-cyanide bath the conductivity was slightly greater, about 9 percent, than when they were plated in the standard copper sulfate electroplating

*They also state that because of silver's characteristic rapid oxidation, the resistivity of the coating increases quickly, even in a short period of time, such as a few months.

Piece	Normalized RF Surface Resistivity	Equivalent IACS Percentage	Plating Current Reversed Periodically	Burnished	Internal Electrodes Used
Original Beryllium Copper Surface					
As delivered	3.3	9.2	-	-	-
Cleaned in Nitric acid	2.5	16.0	-	-	-
Electroplated With Copper					
152	1.27	62.0	No	No	Yes
155	1.23	66.1	No	No	Yes
520	1.15	75.6	Yes	No	Yes
525	1.12	79.7	Yes	No	Yes
Electroplated With Silver					
155	2.15	21.6	No	No	No
155	2.09	22.9	No	No	No
152	1.84	29.5	No	No	Yes
521	1.69	35.0	Yes	No	Yes
525	1.62	38.1	Yes	No	Yes
152	1.34	55.7	Yes	Yes	Yes
523	1.19	70.6	Yes	Yes	Yes

TABLE I

The normalized RF surface resistivity of cast beryllium copper magic tees electroplated with copper and silver.

solution. The major difference between these two baths was that the cyanide solution did not contain certain organic additives. It is thought that these additives, which coat the surfaces of the copper crystals, tend to increase the RF resistivity of the deposit. More will be said about this in the section which is concerned with copper electroformings. The frequency at which these magic tee experiments were carried out was 8.05 GHz.

II. CORRELATION BETWEEN SURFACE ROUGHNESS AND RF SURFACE RESISTIVITY

The skin depth in copper at X-band is approximately 30 microinches. It is therefore apparent that only a very thin surface layer of the conductor is important in carrying current. The properties of this thin surface layer will therefore determine the RF characteristics of the material. Surface properties such as finish, porosity, oxide coatings, work hardening, cleanliness, molecular coatings caused by chemical additives during electroforming, and even the cooling process in the manufacture of cast components can affect the RF resistivity of the material.

The effect of surface roughness, by far the most important, will be considered now. It can be thought of simply as causing the RF current path to be lengthened, which results in a larger RF resistance than would be expected with an ideally flat surface.

A short series of tests were performed to help obtain a better understanding of the actual dependence of the RF resistivity on the roughness of a cast surface. Four methods of improving the surface finish were used:

- 1) Abrasive polishing techniques,
- 2) Etching with a nitric acid which contained additional chemical polishing agents,
- 3) A combination of the abrasive and acid techniques,
- 4) Electropolishing.

Abrasive-Acid Smoothing

All the standard trade techniques for polishing metal surfaces, such as barrel finishing, apply only to external surfaces. However, a novel modification of these practices can be used to effectively smooth the often complex-shaped interior surfaces which are normally encountered in waveguide components. The waveguide pieces to be smoothed were partially filled with a mixture of abrasive and polishing stones,* water, and a mild detergent, then sealed off at its openings and placed in the jaws of a commercial paint shaker. The vibrations of the paint shaker imparted sufficient energy to the stones to smooth the internal surfaces of the waveguide. After this abrasive process, the components were washed and then dipped in acid "A".

Samples treated in this manner exhibited a significant lowering in their surface resistivity as the surface roughness decreased. Table II shows some typical results which were obtained. Also in the table are two samples, V-U and 12-H, which received no abrasive leveling but were polished for approximately eight minutes exclusively in acid "A", and samples 1-H, 10-H, I-U, and 7-H, which did receive abrasive grinding but were cleaned in a bright-dip solution that did not contain any leveling or polishing additions.

The values of the surface finish that are listed in the table are RMS readings in microinches. These were obtained with a surface profilometer which was unable to take the frequency of the surface variation into consideration. Therefore, the numbers for the surface finish should only be used as a measure of surface roughness and not as a reference for comparing surface resistivities of different samples which indicate the same surface roughness.

* The Abrasive Division of Norton Company of Worcester, Mass., was kind enough to supply us with various types of polishing and grinding stones for experimentation inside X-band waveguide components.

In other words, two different samples may record the same surface roughness; however, one surface may have more fine detail in it than the other. Therefore, the finely detailed surface will have a longer RF current path near the surface and also a slightly higher RF surface resistivity.

As seen from Table II, the average improvement in the RF surface resistivity obtained with abrasive-chemical smoothing was about 23 percent, with abrasive smoothing alone, about 16 percent, and with chemical polishing alone, about 19 percent. While these results definitely show a relationship between surface roughness and RF surface resistivity, it must be remembered that the acid treatment tends to dissolve slight surface impurities as well as high spots on the surface.

Electropolishing, the final method used to help smooth the internal surfaces of microwave components, does not appear in the table. This technique was tried on a number of samples; however, no encouraging results were obtained from the various pieces which were tested. Experiments with the waveguide samples failed to achieve a satisfactory surface finish. As it turns out, the optimum voltage in an electropolishing bath is very critical; higher or lower voltages will cause pitting and etching, respectively.⁽¹⁾

III. OTHER CASTING ALLOYS

Chromium Copper

The feasibility of casting microwave components from an alloy with a higher conductivity than beryllium copper was considered worth pursuing. One of the larger microwave casting houses in the area had been experimenting with a casting alloy of chromium and copper. The chromium copper alloy has a DC conductivity of about 75 percent IACS and would indicate that an optimum normalized surface resistivity of about 1.15 was possible for an ideally flat surface. We were supplied with some test cavities cast from this experimental alloy which had undergone various heat treatments. When they were measured at RF, about 9.35 GHz, the normalized surface resistivity of these pieces was found to range in value from 1.56 to 1.82 (i.e., 30 to 40 percent IACS).

Piece	Surface Roughness (in microinches) Broad / Narrow Walls / Walls		Normalized RF Surface Resistivity		Smoothing Technique Used
	Before Smoothing	After Smoothing	Before Smoothing	After Smoothing	
XV/U	60/60	16/17	1.22	1.05	14
17/H	100/100	13/23	1.39	1.07	23
20/H	80/80	15/20	1.37	0.97	29
1/H	100/100	22/30	1.40	1.33	5
10/H	100/100	20/37	1.40	1.29	8
I/U	60/60	15/23	1.21	1.02	16
7/H	114/142	17/35	1.39	1.01	27
V/U	75/75	50/50	1.22	1.05	14
12/H	110/110	70/70	1.40	1.08	23
					Abrasive and Chemical
					Abrasive and Chemical
					Abrasive and Chemical
					Abrasive
					Abrasive
					Abrasive
					Abrasive
					Chemical
					Chemical

TABLE II

Correlating the change in surface roughness with
the change in RF surface resistivity.

Electrolytic-Tough-Pitch Copper

At this point, two other casting houses showed interest in continuing the experimentation into the melt chemistry of other high-conductivity alloys such as electrolytic-tough-pitch copper which has a DC conductivity of 100 percent IACS. One, which I will refer to as casting-house "U", already had casting experience with ETP* copper, and the other, a local firm, which I will refer to as casting-house "H", was willing to share the cost so that they could gain some experience in this field.

Samples of ETP copper castings were secured from both firms and when tested, did indeed have DC conductivities equal to, or greater than, 100 percent IACS. However, the amount of oxygen dissolved in the samples obtained from casting-house "U" was not controlled as much as the casting-house "H" samples, in which the volumes of oxygen and hydrogen dissolved in the copper were regulated quite tightly. The amount of hydrogen in the pieces from casting-house "H" was all but eliminated by maintaining a high oxygen concentration during the melt, since the product of the oxygen and hydrogen concentrations must remain a constant. The copper was then deoxidized by the addition of calcium boride to the melt.

When delivered, these waveguide samples had an internal surface finish which varied from about 60 microinches (casting-house "U") to about 100 microinches (casting-house "H"). Resistivity measurements performed on these samples in their as-delivered condition (i.e., before acid cleaning and surface treatment) yielded a normalized RF surface resistivity of 1.49 for those samples from casting-house "H" and 1.64 for those pieces from casting-house "U". This initial difference in the resistivities is believed to result more from the different concentrations of oxygen dissolved in the respective samples than the difference in roughness since 60 and 100 microinches are both greater than a couple of skin depths.

The effect of smoothing the internal surfaces of these castings can be seen by referring back to Table II, where the samples from casting-house "U" are represented by "U" and the samples from casting-house "H" by "H". Excellent

* Electrolytic-Tough-Pitch

Results were obtained with almost all pieces that underwent either the abrasive-acid treatment or the acid-polishing treatment alone. In fact, all waveguide castings which were treated in one form or another with acid "A" for more than five minutes had normalized surface resistivities within a few percent of the theoretically calculated limit.*

Thus it is possible to have microwave castings with a low RF resistivity. Castings made from ETP copper combined with an acid "A" surface treatment yield RF surface resistivities that are within a few percent of those obtained with certified OFHC copper waveguide.

Generally speaking, the inherent limitation in obtaining cast components with low RF resistivities in a single-step process is the basic roughness of the internal surfaces. With the present choice of raw materials available for the ceramic mold, the best that present investment casting technology can be expected to do today is about a 64-microinch finish.

It was learned, however, that a preformed internal ceramic core can be produced with a very fine surface finish. In this process the ceramic surface becomes glazed and finishes of about 8 microinches have been achieved. At the present time, however, the drawbacks to such glazed cores are their high cost and tendency to interact with the casting alloy.

IV. SURFACE OXIDES AND SURFACE RESISTIVITY

The effect of shelf life on unprotected pieces of copper waveguide such as electroformings, OFHC, and ETP copper castings can be quite significant. Resistivity measurements on samples of OFHC copper waveguide which had been in storage** for 18 months showed an RF normalized surface resistivity equal to 1.24 (65 percent IACS). When these pieces were cleaned in acid "A" for 2 to 5 minutes, the RF resistivity decreased to 1.00 (100 percent IACS).

* See the second footnote on page 3.

** Essentially open to the atmosphere.

Electroformings and OFHC copper samples will show a tendency to oxidize more rapidly than ETP copper castings because of their initial low-oxygen content. For example, increases of 2 to 9 percent have been noted in the RF surface resistivity for ETP copper castings, while some electroformed waveguide samples changed as much as 24 to 44 percent during the same time period, which was approximately three months.

Later tests on unprotected waveguide samples of OFHC and electroformed copper waveguide components which were artificially aged in a special high-humidity, high-temperature atmosphere* showed an increase in the RF surface resistivity of 13 to 14 percent.

Acid Cleaners

As stated earlier, the oxidation can be removed chemically, thus restoring the original value of surface resistivity to the waveguide. Three different acid-cleaning solutions were used for that purpose during these experiments. One, commonly known as "bright-dip", contains a mixture of nitric and sulfuric acids and, when fresh, will etch a copper surface away at the rate of one mil every ten minutes. Another, acid "B", removes oxide coatings without significantly affecting the copper surface beneath. It will etch copper at a rate of one mil every ten hours. A third acid used, acid "A", is a "bright-dip" type of acid which contains a large amount of nitric acid, combined with leveling and polishing agents. Acid "A" etches one mil of copper away every eight minutes when fresh.

The "bright-dip" tank originally used for some of the earlier experiments was open to general laboratory use and thereby illustrated an important point--that contaminants suspended in a solution of dirty acid can be chemically deposited onto the surface of the components intended to be cleaned! This was

* This aging experiment will be described fully in the section concerning protective coatings. Basically, however, the test consisted of cycling the waveguide samples for half the time in a 98-percent relative-humidity atmosphere at 149°F using distilled water, and the other half the time in an oven at 265°F.

discovered accidentally when the RF resistivity of a piece just cleaned in the acid bath turned out to be quite higher than what it was originally.

Hydrogen Firing

Another method which was used to deoxidize waveguide surfaces is called hydrogen firing. In a simple experiment, ETP copper castings were fired in a hydrogen atmosphere for one hour at 1000°F. The average surface finish of these castings before firing was about 26 microinches. After firing, the castings were examined for physical and microwave differences and the following results were noted. The castings from casting-house "U" became blistered; the surface finish increased to 80 microinches; open cracks in the piece could be seen, and the flanges were warped to the extent that they had to be re-machined. The normalized RF surface resistivity for such a piece before firing was 1.18, and immediately after firing measured 1.23; however, when the surface finish was smoothed to what it was before firing, the normalized RF surface resistivity dropped to 1.14. The castings from casting-house "H", however, did not show any appreciable physical change; however, the average surface finish did change from 26 to 45 microinches. When placed in the microwave test setup, it was found that all these samples had suffered large increases in their RF resistivity, much more than could be accounted for by the change in surface finish alone. Before hydrogen firing, the castings had values of normalized RF surface resistivity ranging between 1.40 and 1.70. After firing, they varied between 2.33 and 5.35.

It is possible to explain these results in the following manner. The castings from casting-house "U" were of a high-purity copper, but contained large amounts of oxygen. Therefore, during the hydrogen firing, large volume changes due to water molecules and the high vapor pressure of the deoxidation of cuprous oxide severely attacked and opened the crystal boundaries, thus causing the surface to roughen. This process is often called "embrittlement".⁽¹³⁾ Since the copper was now deoxidized, a slight improvement in the surface resistivity would be expected when the roughened surface was returned to its original state, as with the pieces from casting-house "U". The samples from casting-house "H",

on the other hand, originally contained only a very small amount of oxygen because of the addition of the calcium boride deoxidizer to the melt; but, enough oxygen was still retained to form oxides of calcium and boron, which were then held in suspension. These oxides as well as those of calcium boride do not significantly affect the RF resistivity. However, after being reduced by the hydrogen firing, the calcium and boron without their oxygen bonds could have increased the RF resistivity considerably.

Summarizing, acid "B" is best suited for those pieces of chemically pure copper waveguide which have good internal surface finishes. However, most components contain some impurities or usually their purity is an unknown quantity. Therefore, as in the case of OFHC copper waveguide, where the surface has oils and other die contaminants in it, and castings, where small amounts of impurities may lie near the surface, a strong acid is necessary to etch some of the copper away. The leveling properties and overall performance of acid "A" make it the best "all-around" choice for cleaning OFHC, castings, and other copper components where surface and subsurface contaminants must be removed. When used on electroformings for periods of two to five minutes, acid "A" did not increase the RF surface resistivity and even had a slight tendency to lower it.

Hydrogen firing must be reserved for those situations that necessitate just oxide removal. Only drawn or fabricated pieces of waveguide can be subjected to this treatment since "embrittlement" will spoil electroformings as well as castings. One must also be careful of soldered joints and contaminants which may foul the hydrogen oven. In all, hydrogen firing was not the most practical nor successful cleaning process used.

V. ELECTROFORMINGS

Excellent internal surface finishes for most waveguide components can be achieved with electroforming techniques. This is because the internal surface finish of the component is determined by the external surface finish of the mandrel, which can be polished rather easily and accurately. Mirror-like

internal surface finishes of approximately four to eight microinches are easily obtained for those electroformings made on aluminum mandrels.

Waveguide components electroformed on stainless steel mandrels may have a slightly rougher transverse finish because of the method which is used to extract the mandrels. The stainless steel mandrels are pulled out of the components which sometimes leave "mandrel marks" down the length of the interior surface of the waveguide. Aluminum mandrels, on the other hand, are removed chemically with caustic soda (sodium hydroxide). Obviously, stainless steel mandrels are made for only those shapes that lend themselves to retrieval of the mandrels, and whenever repeatability is important.

Resistivity measurements on electroformings made from aluminum mandrels show that the normalized RF surface resistivity of the finished piece after an acid dip is often a few percent lower than the theoretically calculated limit.* And as mentioned earlier in the section concerned with electroplated castings, the measured normalized RF surface resistivity for those electroformings made on stainless steel mandrels is slightly higher, about two to nine percent, than those made on aluminum mandrels. However, the resultant electroformings made on stainless steel mandrels still have excellent RF resistivities which are within a few percent of the calculated limit.

The slight difference in resistivity achieved by these two baths is believed to be caused by the difference in the initial striking of the copper to the mandrel. Aluminum mandrels are normally struck in a rochelle salt, copper cyanide bath and later transferred to the standard copper sulfate bath if the electroforming necessitates a thick deposit, since thick cyanide copper deposits tend to be nodular in structure. On the other hand, it is normal practice for the stainless steel mandrels to go immediately into a copper sulfate plating bath for the entire electroforming process.

The basic difference between these plating solutions is that certain organic compounds are added to the copper sulfate bath to help it produce a

* See second footnote, page 3.

thick copper deposit which is smooth, dense, and finely grained. These colloidal additives tend to coat the copper crystals and thus limit the size to which they may grow. It is believed that this coating action at the crystal interfaces increases the RF resistivity of the deposit.

Electroformed microwave components made on either aluminum or stainless steel mandrels will have the lowest RF resistivity of all the practical fabrication techniques. The mirror-like surfaces obtainable, along with the high-purity copper deposits^{*} inherent in the process, make electroformed components almost ideal.

VI. WAVEGUIDE PROTECTIVE COATINGS

Once a low RF surface resistivity and a good surface finish have been achieved, it is important to protect the waveguide surface from deterioration because of environmental conditions. Tests on unprotected copper waveguide subjected to different external conditions show that the RF resistivity does increase sufficiently to warrant protective measures.

The RF surface resistivity of some electroformed copper waveguide samples which were exposed to normal atmospheric conditions for a period of three months and received constant handling and usage degraded as much as 24 to 44 percent. Other samples were artificially aged by cycling between a 98-percent relative humidity atmosphere at 149°F using distilled water and an oven set at 265°F. These test pieces spent half their time in the high humidity chamber and half in the high-temperature oven. Electroformings and pieces of OFHC copper waveguide placed in this cycle for one month degraded about six percent in RF resistivity and after six months a total degradation of 13 to 14 percent was measured.

At this point it is necessary to say that the results of this artificial aging must stand by themselves. This is because it is almost impossible to make any sort of accurate comparison or correlation between the controlled

*The cleanliness of the plating solution is of paramount importance. A dirty bath can cause organic matter to become entrapped in the deposit, which will then appear to have more loss than would normally be expected.

environmental conditions of this test and the conditions which would normally be encountered in a practical and operational system. The data obtained from this artificial aging experiment is nevertheless interesting and pertinent and therefore is included here for those reasons.

Coatings

The following is a list and brief description of the waveguide protective coatings which were measured. The list contains two low-loss dielectric coatings and eight high-conductivity metallic coatings. All the coatings were applied to freshly electroformed copper waveguide samples.

- (1) Chromate* - A carefully controlled iridite-type process.**
This coating requires no curing and has a single-layer thickness of approximately 100-200 microinches.
- (2) "S-4" - A silicon-based metal protectant. This dielectric coating requires a fifteen-minute curing period at 150°C and hardens to a thickness of approximately 100 microinches.
- (3) Gold displacement - This is a chemical displacement process in which one microinch of gold displaces an amount of copper and adheres to the waveguide surface without the use of any electrode. This immersion process has the advantage of covering complex internal configurations evenly, including the inside corners, which is difficult to do by standard electroplating techniques. Since the skin depth at 7.57 GHz (the measurement frequency) is about $3\frac{1}{4}$ microinches, the one-microinch gold coating should be electrically transparent.
- (4) Nickel reduction - This process is mainly a reduction of nickel and not a displacement process as the gold and silver were. The nickel precipitates out of solution and coats the copper with a thicker film than can be achieved with either

* Thickness is not an electrical problem for these two dielectric coatings because the skin depths for both are in the order of meters.

** Applied according to Raytheon Specification No. VA296 MS596, Type 2.

the silver or gold displacement. However, like the other immersion processes, no electrodes are necessary. A coating six microinches deep is not difficult to realize using this method. With a skin depth of 25 microinches at this frequency, the six-microinch nickel coating should influence the total resistivity in only a small fashion. However, it must also be remembered that the nickel coating is magnetic and may cause some inconveniences for that reason.

- (5) Gold reduction - This is a relatively new process on the market, and is a reduction of gold out of solution similar to the nickel. This "electroless" process can deposit approximately eight microinches of gold per minute on any conducting surface which is dipped into the solution. The particular samples which were used had a coating thickness of about eight microinches.
- (6) Gold-over-silver immersion sandwich - In this case, two tenths of a microinch of silver were displaced onto the copper waveguide samples by simple immersion (no electrodes) with an additional one-tenth of a microinch of immersion gold displaced on top of the silver forming a gold-over-silver sandwich. At 7.57 GHz, the thicknesses of these coatings are so small when compared with their respective skin depths--gold, $3\frac{1}{4}$ microinches, and silver, 29 microinches--that they can be considered electrically invisible.
- (7) Gold-over-nickel immersion sandwich - A coating of 6 microinches of nickel was precipitated out of solution on the copper waveguide and covered with a $\frac{1}{4}$ -microinch layer of displaced gold in a manner similar to the gold-over-silver sandwich.
- (8) Gold flash - A thin layer of 25 microinches of gold was electroplated on the copper waveguide with an internal electrode to form this coating.

- (9) Silver flash - Silver was electroplated on the copper waveguide samples to a depth of 25 microinches using internal electrodes.
- (10) Rhodium-over-silver electroplating - Rhodium does not make a strong chemical bond with copper and therefore silver, which will bond to the rhodium, has to be used as the substrate. However, such a thick layer of silver is usually required, 250 microinches in this case, that the rhodium flash does not protect the copper at all, but really the silver.

Table III contains a list of these coatings and their corresponding effect on the normalized RF surface resistivity of the waveguide specimens. Also included in Table III are the results of one-month's cycling in the artificial aging chambers and the final normalized RF surface resistivity* attained by these samples.

In some earlier measurements two other dielectric coatings were tested. A "DC-6" varnish was used which had to be cured for 16 hours at 350°F. Teflon was the other coating and it had to be bonded to the waveguide in two separate layers to obtain a total thickness of one mil. Teflon also had to be cured, but for only 33 minutes. However, the curing temperature was quite high at 650°F. Neither coating was very successful, as the "DC-6" varnish caused a 60-percent increase in the RF surface resistivity and the teflon a 54-percent increase.

* The normalized surface resistivities listed in Table III were adjusted so that the initial r_s would be unity for all the samples in their uncoated condition. Practically all the electroformed samples had initial values of r_s which varied between 0.94 to 0.98.

Coating Type	Coating Thickness Microinches	Coating Percent Change	Artificial Aging: Percent Change	Final Normalized Surface Resistivity
1. Nickel	6.0	0.0	0.0	1.00
2. Chromate	100	0.0	0.6	1.01
3. Rhodium/Silver	3.0/250	1.0	1.0	1.02
4. "S-4"	100	0.0	4.3	1.04
5. Gold (reduction)	8.0	1.3	3.5*	1.05
6. Gold (displacement)	1.0	1.3	3.4	1.05
7. Silver (electroplate)	25.0	2.6	2.2	1.05
8. Gold (electroplate)	25.0	2.4	3.0	1.06
9. Gold (dis.)/Nickel	4.0/6.0	8.4	12.8	1.32
10. Gold (dis.)/Silver	0.1/0.2	43.7	21.5	1.75

No Protective Coating

Electroformed copper One month artificial aging	-	-	6.0	1.06
Electroformed copper Three months shelf life	-	-	20 to 40	1.20 to 1.40
OFHC - one month artificial aging	-	-	12.8	1.13
OFHC - 18 months shelf life	-	-	24	1.24

* This specimen was subjected to the artificial aging test for a period of six months instead of the one month given the other coatings.

TABLE III

Degradation of the Normalized Surface Resistivity Caused
by Protective Coatings and an Artificial Aging Process.

Based on the results of these measurements, it seems that one can protect a waveguide surface for a fairly long time without encountering any significant increase in RF resistivity. Either the dielectric chromate coating or the metallic nickel coating would be an excellent choice. As for the rest of the coatings in the test, the "S-4" coating was slightly degraded by the high temperatures and humidity of the aging process; however, it should still be considered as a substitute for the chromate coating. Circumstances might make it necessary, however, to choose a metallic coating other than nickel because of the magnetic problems that could be encountered.* (The relative permeability of nickel has been measured at 7.57 GHz⁽¹³⁾ and found to be approximately 5.5.) An excellent second choice for a metallic protective coating would be gold, because of its reluctance to form oxides easily.

The three different techniques which were used to apply gold to the waveguide samples, namely displacement, reduction and electroplating, provided some interesting results. The most promising of the three was the gold reduction or "electroless-gold" method. In this process the amount of gold which could be precipitated out of solution was controlled fairly easily and the thickness of the deposit was not limited for most practical situations. A coating thickness of 10 to 15 microinches seems optimum at this time. The displacement process, on the other hand, was limited to a thickness of about one microinch, which appears to be too thin to provide any sort of effective environmental protection for copper. Also, it was thought that the displacement process created a slightly resistive boundary layer, which did not form

* It was learned that a special heat-treatment process will cause the nickel coating to lose its magnetic properties. Unfortunately, it was too late to obtain any samples for testing which could be included in this paper.

during the reduction method. In the electroplating-flash technique it was considerably more difficult to control the plating thickness on the internal surfaces. The samples which were used in this test had deposits of gold between 20-30 microinches in thickness, which was too thick in some areas for the gold to remain electrically transparent.

There are certain other facets to gold protective coatings of which one should be aware. Porosity, for one, may seriously affect the protective qualities of the gold coatings by making it easier for the underlying surface to corrode. Porosity is not only a function of the coating material and its deposition technique, but also of the base surface (i.e. its substance, roughness, cleanliness, etc.). Diffusion of the gold coating into the base metal is another factor which is often discussed. However, the effect of diffusion, for all practical purposes, is insignificant; even after 2-3 years, the change in the quantity of gold would only be 2-3 parts in a thousand at 20°C. Still, gold coatings over copper surfaces are known to dull after a period of time due to the copper found at the surface of the gold. The cause of this apparent movement of the copper to the gold's surface is more likely the porosity of the gold deposit than its diffusion rate. Additional information concerning the porosity of electrodeposited coatings can be obtained from the recent work of Walton.⁽²²⁾

The two sandwich-layer coatings, gold over silver and gold over nickel, did not work out satisfactorily. It is believed that the problem lies in the boundary between the gold and silver layers and between the gold and nickel layer.

The type of coating combining a protective rhodium flash over a silver electroplated copper surface has been reliably used for a number of years. The resistivity measurements showed that this coating provides excellent protection with low RF loss. However, a drawback to this type of coating is that it can be very expensive for sections of waveguide with complex internal configurations. This is because platinum electrodes are required to deposit the rhodium flash. Secondly, it is a lengthy and time-consuming operation since another set of internal electrodes of steel must be fabricated to deposit the silver.

In choosing a waveguide protective coating there is always a decision to make between a dielectric and a metallic coating. Table IV lists some basic advantages and disadvantages for each of these types of coatings.

	Dielectric Coatings	Metallic Coatings
<u>Advantages</u>	<ol style="list-style-type: none"> 1. Easily and quickly applied. 2. Low cost. 3. No thickness problem. 	<ol style="list-style-type: none"> 1. No series loading at flanges. 2. Reduction and immersion coatings have the same application advantages as dielectrics in addition to no inside corner problem and no need for internal electrodes.
<u>Disadvantages</u>	<ol style="list-style-type: none"> 1. Must have low loss tangent 2. If dielectric is not completely removed from flange faces, series loading will occur. 	<ol style="list-style-type: none"> 1. Skin depth problem 2. Electroplated coatings have an inside-corner problem and need internal electrodes.

TABLE IV

Dielectric Versus Metallic Protective Coatings

CONCLUSION

The information gathered during this program can be briefly summarized as follows.

The RF surface resistivity of beryllium copper castings has been successfully reduced by the use of electroplating techniques. It has been found that factors such as surface roughness, porosity, chemical cleanliness, and electroplating chemistry often limit the degree of improvement which can be attained. Best attempts to date have been obtained from castings electroplated with copper rather than silver. Such components, when measured, were within 20 percent of the RF surface resistivity of pure, unalloyed copper. The RF surface resistivity of beryllium copper castings as delivered from the manufacturer is approximately 3.3 times greater than that of copper.

There is a direct relationship between surface roughness and RF surface resistivity. Low-loss conditions were achieved when the internal surface roughness of waveguide components was smoothed to less than a skin depth in the material. Good results were obtained from electroplated castings when that philosophy was adhered to.

Excellent castings of electrolytic-tough-pitch copper have been secured which can be brought to within a few percent of the RF resistivity of copper. It is usually necessary to acid clean these pieces and often the internal surface must be smoothed. A simple leveling technique has been developed which can smooth the internal walls of X-band components to about 20-30 microinches.

Surface oxides, local surface impurities and contaminants caused from the handling of pieces can increase the surface resistivity of OFHC copper and electroformed components by as much as 20 to 40 percent in the space of three to four months. A strong nitric acid cleaner, such as acid "A", has been found to remove practically all these coatings and return the resistivity to its original value.

The low value of resistivity of OFHC copper and its good surface finish make it an excellent choice for the fabrication of waveguide components. Electroformed copper components made on polished mandrels and in a clean bath will yield waveguide components with the lowest RF surface resistivity attainable at this time.

Tests on various protective coatings have indicated two coatings which will each do an excellent job of protecting a waveguide surface from deterioration. They are a metallic-immersion nickel coating of less than 10 micro-inches and a dielectric chromate-type coating. As second choices, a 10 micro-inch, "electroless-gold" coating and "S - 4", a silicone-metal protectant, have proven acceptable.

Lastly, there are two areas which could benefit from additional development. More work should be done to lower the RF resistivity of electroplated castings even further than that attained in this work and many more protective coatings, both metallic and dielectric, should be investigated. Two coatings, which come to mind quickly, are the nickel coating which has undergone the special heat treatment that is said to reduce its magnetic properties and a thin chromium coating of approximately 10 microinches in thickness.

APPENDIX I

Q METER OPERATION

The values of RF surface resistivity which were used throughout this report were calculated from measurements of the unloaded Q of a three-section waveguide cavity whose middle section was fabricated from the material under investigation. The ends of the cavity consisted of a quarter-wave iris and a quarter-wave short circuit electroformed from ETP copper. The iris and short were designed to produce a current null at the flange interfaces. Knowing the unloaded Q and the resonant frequency of the cavity from an X-band Q meter, which was built specifically for this study, the surface resistivity was determined by working out the expressions for the losses and stored energy in the cavity. These derivations will be presented at a later point in the Appendix.

X-Band Q Meter

The Q meter, as shown in Fig. A-1, can measure the resonant frequency of the test cavity, the 3 db, or equivalent, bandwidth and the VSWR of the cavity on resonance. These three quantities are sufficient to determine the unloaded Q of the cavity and also the unknown RF surface resistivity of the middle section of the cavity. Specifically, for an undercoupled cavity, the unloaded Q is calculated from ⁽¹⁴⁾

$$Q_o = \frac{f_o}{\Delta f} \left(1 + \frac{1}{VSWR} \right) \quad (A-1)$$

where f_o is the resonant frequency, Δf is the 3-db bandwidth, and the VSWR of the cavity is determined on resonance.

Figure A-2 shows a block diagram of the Q meter, which will be helpful in understanding the general operation of the circuit as described below. A more detailed description of the individual parts and functions of the Q meter will be found under the section "Circuit Operation".

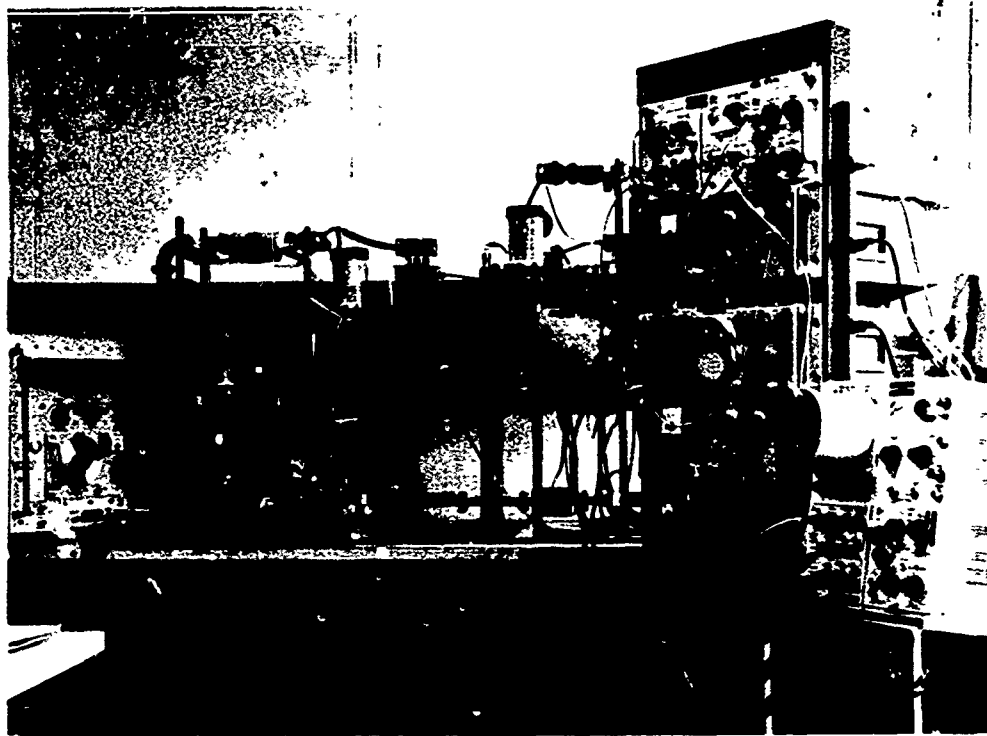


Fig. A-1(a) X-band Q meter equipment.

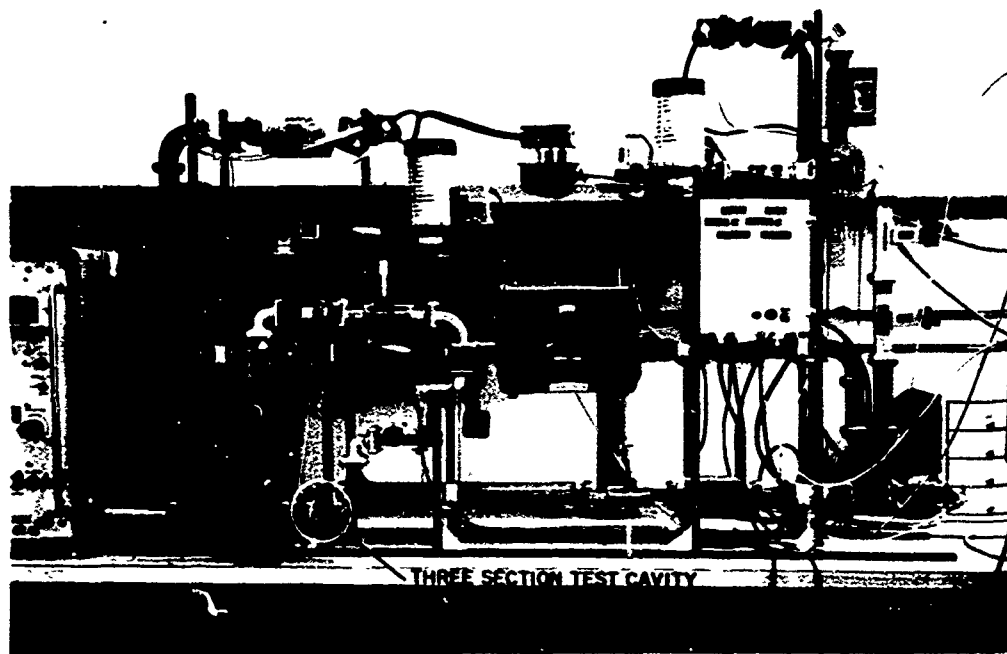


Fig. A-1(b) Q-meter microwave components.

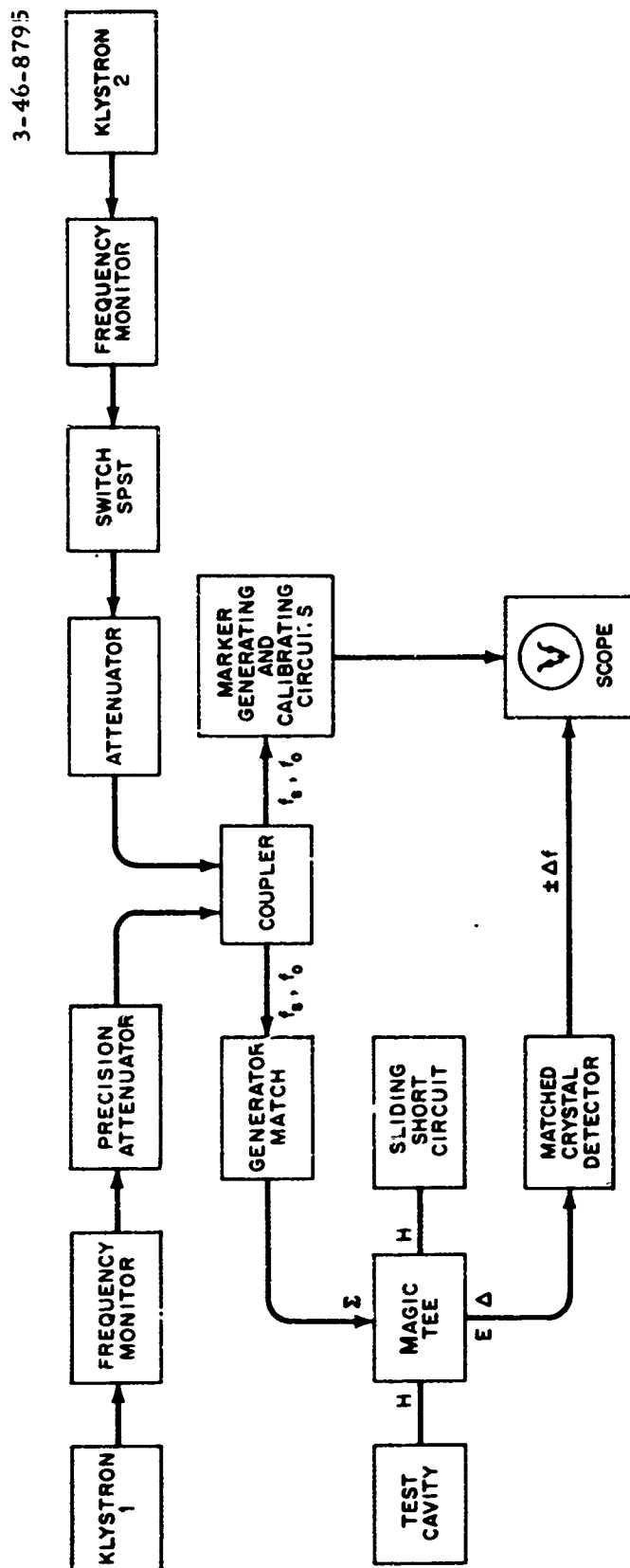


Fig. A-2 X-band Q meter block diagram.

Klystron No. 1 generates a frequency f_s which is centrally swept about the resonant frequency of the cavity, f_o . This swept frequency is combined with a fixed frequency from klystron No. 2 for the purpose of generating frequency markers. Klystron No. 2 is tuned to the resonant frequency of the cavity in order that these frequency markers can be centered on the cavity response curve. The cavity response curve, which originates from the difference arm of the magic tee, is proportional to $(1 + \rho_c)$ when the sliding short circuit is adjusted to the off-resonance plane of the cavity. This means that the test cavity and the short circuit are initially equal line lengths away from the magic tee; ρ_c is the reflection coefficient of the cavity.

The frequency marker circuit, see Fig. A-3, generates audio pulses which are directly proportional on a time scale to the frequency of the incoming video FM signal. This video signal is the detected difference between the fixed frequency of klystron No. 2, f_o , and the instantaneous swept frequency of klystron No. 1, f_s . The output pulses of this circuit are then used to intensity modulate a CRO as frequency marker pips.

Circuit Operation

The most important and critical measurement performed with the Q meter is the determination of the 3-db bandwidth of the test cavity response curve. Figure A-3 shows a detailed diagram of the marker generating and calibrating circuit. The signal out of the coupler contains both the swept frequency, f_s , and the fixed frequency, f_o . A crystal detector feeds the difference, now a video FM signal, into the receiver. As the video signal sweeps by the frequency to which the receiver is tuned, an audio pulse is generated which is transmitted to the output of the receiver. Since the video signal sweeps by the receiver frequency twice during one modulation cycle of klystron No. 1, the receiver output will generate two audio pulses for every one modulation cycle. Thus, there is a direct one-to-one correspondence between the frequency of the video FM signal and time interval between the two audio pulses that is adjustable. This interval therefore corresponds to exactly twice the receiver frequency setting, and these audio marker pulses can then be used to intensity

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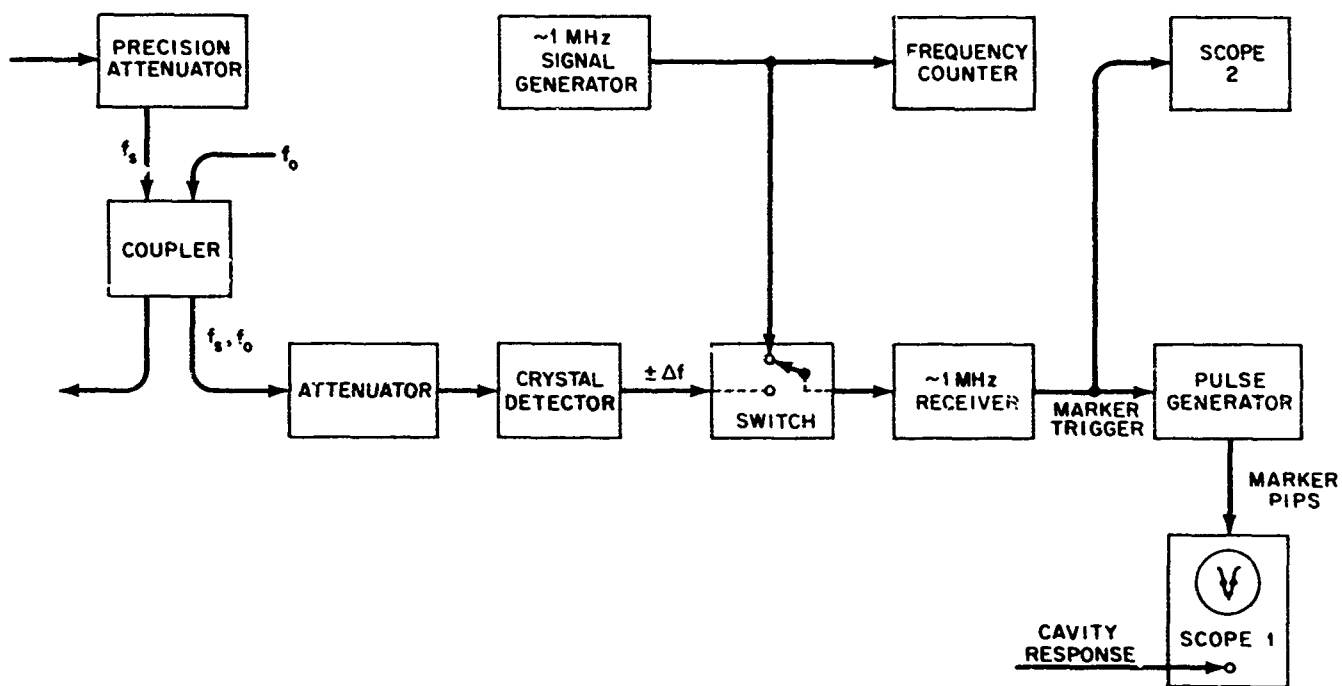


Fig. A-3 Marker generating and calibrating circuits.

modulate the cathode of the CRO which is displaying the response curve of the test cavity. To sharpen up these audio pulses, the output of the receiver is used to trigger a unit pulse generator which in turn feeds the cathode of the CRO as the actual marker pulses.

A frequency counter can then be used to measure the receiver frequency with more accuracy than could be obtained by just reading the receiver dial visually. Once the receiver has been adjusted to the desired 3-db bandwidth, as determined visually on the CRO, the input of the receiver is then switched to a signal generator whose output is being monitored by the frequency counter. The BFO (Beat Frequency Oscillator) of the receiver is switched on and the signal generator adjusted until a zero beat is obtained visually on a second CRO. The receiver frequency can then be read directly off the counter with far greater accuracy than the receiver dial could provide.

VSWR Measurement

When the line lengths between the magic tee and the sliding short, and the magic tee and the test cavity are equal, then the signal out of the difference arm of the tee is approximately proportional to $(1 + \rho_c)$, where ρ_c is the reflection coefficient of the cavity. If the short circuit is then moved a quarter wavelength so that the line lengths differ electrically by a half wavelength for a round trip, then the signal from the difference arm becomes approximately proportional to $(1 - \rho_c)$. This approximation will be shown to be valid to within one percent in the error analysis which appears in Appendix II.

It is therefore very convenient to take the logarithmic difference of these two signals since it would equal

$$20 \log \left(\frac{1 + \rho_c}{1 - \rho_c} \right) \quad , \text{ or } 20 \log (\text{VSWR})_{\text{cavity}}$$

at resonance. This logarithmic difference can be accomplished easily with the precision attenuator in the circuit. Noting the power level at f_0 on the response curve for one of the two positions of the short circuit, the attenuator can be adjusted to return the curve to that same level when the short circuit

is moved to the other position. Thus, the VSWR of the cavity at resonance can be read directly in db from the precision attenuator as the difference between the two settings.

Matching the Generator

The existence of the sliding short circuit on one of the H-arms of the magic tee makes it a very simple matter to tune out the generator mismatch. From Fig. A-4, it can be seen that by moving the sliding short, the phase of the reflected wave from the isolator will vary. Thus, as the sliding short circuit is moved back and forth, the signal detected at the output of the 10 db coupler will be the sum of the incident forward power and a ripple caused by the reflection from the isolator. The slide screw tuner can then be adjusted to produce a flat response from the coupler while the sliding short is being moved.

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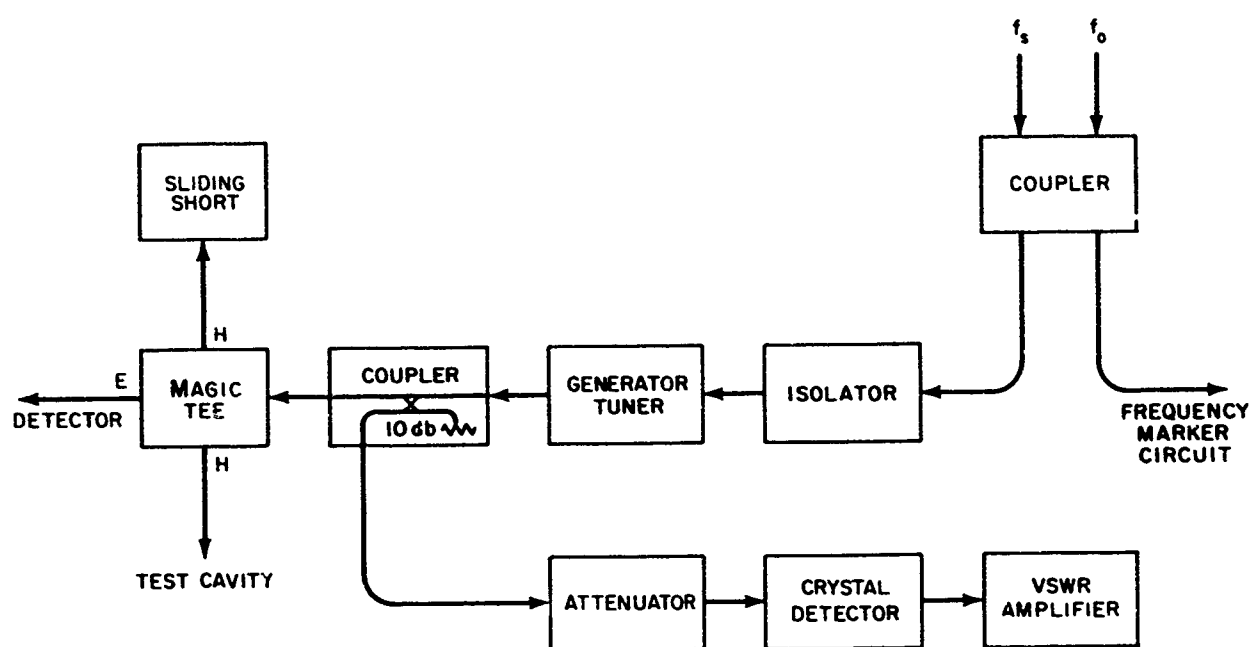


Fig. A-4 Generator matching circuit.

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$$a = 1.122"$$

$$d = 3.235"$$

$$Z_1 = 0.539"$$

$$b = 0.497"$$

$$g = 1.078"$$

$$Z_2 = 2.697"$$

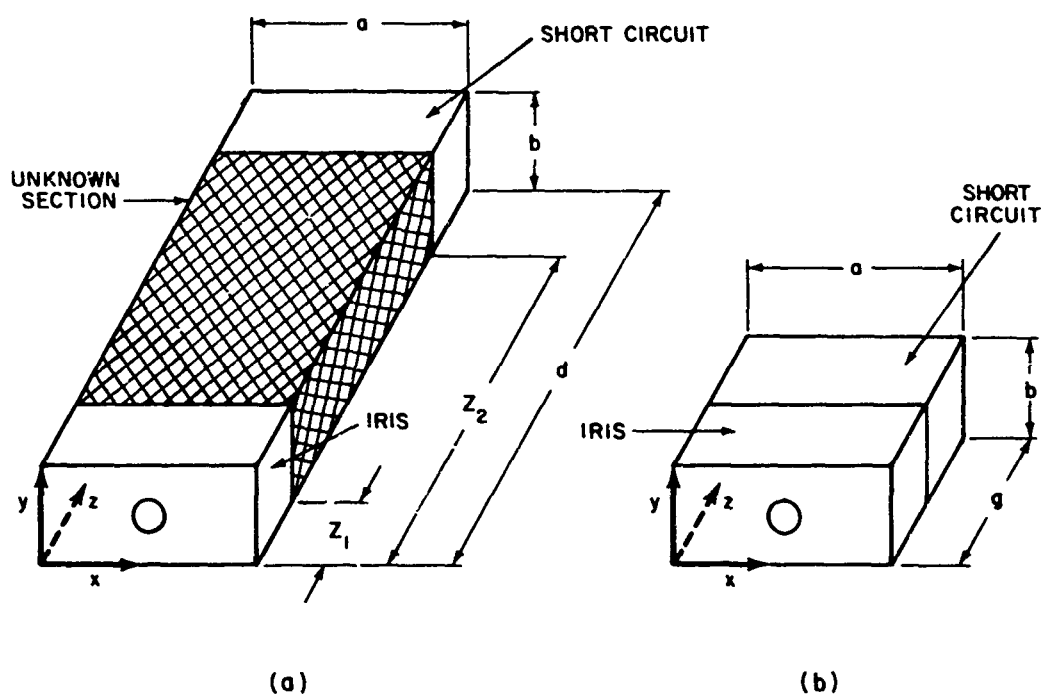


Fig. A-5(a) Three-section test cavity. Fig. A-5(b) Iris-short cavity.

APPENDIX II

DERIVATION OF SURFACE RESISTIVITY

A. The Three-Section Cavity

The unknown surface resistivity of the middle portion of the three-section cavity, as shown in Fig. A-5(a), is determined in a manner similar to that for the simple one-section cavity in Ramo-Whinnery.⁽¹⁵⁾ The only variation from that method is the compensation for the different resistivities of the end pieces which make up the cavity and the use of a higher-order mode in the Z direction. Using the unloaded Q of the complete three-section cavity, it is possible to find the surface resistivities in question. The definition of the unloaded Q of a cavity can be written as

$$Q_o = \frac{\omega_o U_o}{W_L}, \quad (A-2)$$

where ω_o is the resonant angular frequency, U_o is the stored energy, and W_L is the power loss of the cavity.

The stored energy is determined by evaluating the maximum stored electric energy as given by

$$U_o = (U_E)_{\max} = \frac{\epsilon_o}{2} \int_0^d \int_0^b \int_0^a |E_y|^2 dx dy dz. \quad (A-3)$$

The fields in the cavity are as presented in Ramo-Whinnery⁽¹⁵⁾ except where modified for higher-order modes in the Z direction.

$$E_y = E_o \sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{n\pi z}{d}\right), \quad (A-4)$$

$$H_x = -j \frac{E_o}{\eta} \frac{n\lambda_o}{2d} \sin\left(\frac{\pi x}{a}\right) \cos\left(\frac{n\pi z}{d}\right), \quad (A-5)$$

$$H_z = j \frac{E_o}{\eta} \frac{\lambda_o}{2a} \cos\left(\frac{\pi x}{a}\right) \sin\left(\frac{n\pi z}{d}\right). \quad (A-6)$$

The factors in the above equations are: E_0 , an arbitrary constant equal to the peak electric field; η , the free-space impedance equal to 120π ; λ_0 , the resonant wavelength; and n , the number of half guide wavelengths in the Z direction.

E_y can now be substituted into A-3 and the resultant stored energy is:

$$U_0 = \epsilon_0 E_0^2 \frac{abd}{8} \quad (A-7)$$

The power loss in each waveguide wall can be calculated from the currents in that wall⁽¹¹⁾ or

$$W_L = \frac{1}{2} R_s |J|^2, \quad (A-8)$$

where R_s is the surface resistivity and J is the current density in the wall. The current densities⁽¹¹⁾ can be derived from the magnetic fields by

$$\vec{J} = \vec{n} \times \vec{H} \quad (A-9)$$

where \vec{n} is a unit vector perpendicular to the conductor surface, pointing into the adjoining dielectric region. \vec{H} is the peak magnetic field at the surface. Therefore the losses in the cavity can be summed up by considering all the currents in each wall, or in equation form,

$$W_L = \frac{(R_s)_{ys}}{2} \left\{ 2 \int_0^b \int_0^a |H_x|^2 dx dy + 4 \int_0^{z_1} \int_0^a \left[|H_x|^2 + |H_z|^2 \right] dx dz + \right. \\ \left. 4 \int_0^{z_1} \int_0^b |H_z|^2 dy dz \right\} + \frac{(R_s)_x}{2} \left\{ 2 \int_0^{z_2} \int_0^b |H_z|^2 dy dz + \right. \\ \left. + 2 \int_0^{z_2} \int_0^a \left[|H_x|^2 + |H_z|^2 \right] dx dz \right\} \quad (A-10)$$

In the equation above, the terms involving the surface resistivity of the iris and short sections, $(R_s)_{is}$, come respectively from the end walls, the top and bottom walls, and the side walls. In the group of terms for the unknown middle section modifying $(R_s)_x$, the first term is for the side walls and the second for the top and bottom walls. After integration, Eq. A-10 becomes

$$W_L \left[\frac{2\eta}{E_o \lambda_c} \right]^2 = \left\{ \frac{(R_s)_{is}}{2} \right\} \left\{ \frac{\eta_{ab}^2}{d^2} + \frac{\eta_a^2}{d^2} (Z + S) \right\} \Big|_0^{Z_1} \\ + \left\{ \frac{1}{a} + \frac{2b}{a^2} \right\} (Z - S) \Big|_0^{Z_1} \\ + \frac{(R_s)_x}{2} \left\{ \left(\frac{b}{a^2} + \frac{1}{2a} \right) (Z - S) \right\} \Big|_1^{Z_2} + \frac{n_a^2}{2d^2} (Z + S) \Big|_{Z_1}^{Z_2} \quad (A-11)$$

$$\text{where } S = \frac{d}{2n\pi} \sin \left(\frac{2n\pi Z}{d} \right), \quad (A-12)$$

and $(R_s)_{is}$ is the surface resistivity of the iris and short material, which were simultaneously electroformed in the same copper sulfate bath. $(R_s)_x$ is then the surface resistivity of the unknown sample.

When the dimensions of the cavity, which are given in Fig. A-5, are inserted into Eq. A-11, and combined with Eqs. A-2 and A-7, the following expression for the unknown surface resistivity results:

$$(R_s)_x = G \frac{f_o^3 10^{-27}}{Q_o(x)} - H(R_s)_{is} \quad (A-13)$$

where $G = 0.9088$ and $H = 0.6673$.

It is seen from Eq. A-13 that a measurement of the surface resistivity of the iris and short material is necessary to finally solve for the unknown resistivity. This is done simply by removing the middle section of the cavity and measuring the unloaded Q of the cavity consisting of the quarter-wave iris and

short circuit bolted together. Since its resistivity will not change significantly in a short period of time, the iris-short cavity, Fig. A-5(b), need only be measured once each day during a series of measurements on unknown samples.* The relationship between the unloaded Q of the single material cavity of the iris and short and its resistivity is found by modifying the following equation. (1c)

$$\frac{Q_o \delta}{\lambda_o} = \frac{(b/2)(n^2 a^2 + g^2)^{3/2}}{n^2 a^2 (g + 2b) + g^3 (a + 2b)} \quad (A-14)$$

The following equations which can be found in Ramo-Whinnery⁽¹¹⁾ demonstrate the relationship that exists between the skin depth, δ , the conductivity, σ , the permeability, μ_o , and the surface resistivity, R_s .

$$\delta^2 = \frac{1}{\pi f_o \mu_o \sigma} \quad (A-15)$$

$$R_s = \frac{1}{\sigma \delta}$$

After inserting the dimensions of the iris-short cavity into A-14 and then combining it with A-15, an expression for the resistivity of the iris and short cavity can be found in terms of its unloaded Q.

$$(R_s)_{is} \cong A (Q_o)_{is} \quad (A-16)$$

where $A = 198.7719$.

Using Eq. A-16, the expression for the unknown resistivity (Eq. A-13) now contains only parameters which can be measured, namely the resonant frequency, the unloaded Q of the three-sectioned cavity and the unloaded Q of the iris-short cavity.

To create a simple system of evaluation and comparison of the data taken, the unknown resistivity $(R_s)_x$ was normalized to the resistivity of pure copper

* As a check on the consistency of the data obtained from the Q meter over a period of time, it was decided to keep the iris and short sections in a vacuum chamber between tests. When a new series of tests were required, the iris and short were removed from their vacuum environment and placed in the Q-meter circuit for a test measurement. In a year's time, the measurement of the unloaded Q of this special iris and short cavity varied only 1% from the average.

which is given by⁽¹¹⁾

$$(R_s)_{Cu} = 2.61 \times 10^{-7} \sqrt{f_o} \quad (A-17)$$

Combining A-16 and A-17, the equation for the normalized surface resistivity of the unknown sample results.

$$(r_s)_x = C \frac{f_o^{5/2}}{(Q_o)_x} - \frac{D}{(Q_o)_{is} \sqrt{f_o}} \quad (A-18)$$

where

$$C = 0.3482 \text{ and } D = 50821.$$

The resonant frequency in the above equation is in units of hundreds of megacycles per second. Finally, the resonant frequency of the iris-short cavity was designed to be the same as the resonant frequency of the three-sectioned cavity, which has the unknown section inserted between the iris and short.

B. Magic Tee Cavity

Another phase of this study involved determining the RF resistivity of electroplated magic tees. The surface resistivity of the particular coating can be calculated from three sets of Q measurements. The calculation assumes that the surface resistivity of the original beryllium copper castings is known or can be found. Conveniently, the resistivity of cast beryllium copper can be determined by using the three-section cavity method, just described, with test castings supplied by the same manufacturer who cast the magic tees. The variation from lot to lot of the casting material cannot be taken into account; therefore, this method is only approximate, but should prove to be fairly reliable and accurate.

The three sets of measurements necessary are:

A. First, the quarter-wave iris and short circuit are measured as a cavity; the unloaded Q, $(Q_o)_{is}$, the external Q, $(Q_c)_{is}$, and the singly loaded Q, $(Q_L)_{is}$, are then determined from the data and Eq. A-19.⁽¹⁷⁾

$$\frac{1}{Q_L} = \frac{1}{Q_O} + \frac{1}{Q_e} \quad (A-19)$$

B. Second, the three-section cavity made up of the iris, short and the beryllium copper magic tee* is measured. The unloaded Q, $(Q_O)_{EC}$, the external Q, $(Q_e)_{BC}$, and the singly loaded Q, $(Q_L)_{BC}$, are then determined. At this point it is necessary to look at the definition of the external Q,

$$Q_e = \frac{\omega_o U_o}{W_s} \quad (A-20)$$

where W_s is the power loss in the circuit external to the cavity. The other factors are as defined in Eq. A-2. Based on this definition of the external Q, it is possible to say that

$$\frac{(Q_e)_{BC}}{(Q_e)_{is}} = \frac{(U_o)_{BC}}{(U_o)_{is}} \quad (A-21)$$

assuming that the resonant frequency is the same in both cases, which it is designed to be, and that the losses in the external circuit are the same for both cases, which is valid.

The expression for the unloaded Q of the iris-short cavity, Eq. A-2, can be rewritten as

$$(Q_O)_{is} = \frac{(U_o)_{is}}{A(R_s)_{is}} \quad (A-22)$$

where $A(R_s)_{is}$ is an expression for the ohmic losses in the iris and short.

* The interior surface of the magic tee should be cleaned so that an effective comparison can be made later, after the tee is electroplated.

Similarly, the unloaded Q of the beryllium copper magic tee cavity can be written as

$$(Q_o)_{BC} = \frac{(U_o)_{BC}}{A(R_s)_{is} + B(R_s)_{BC}} \quad , \quad (A-23)$$

where $A(R_s)_{is}$ and $B(R_s)_{BC}$ are expressions for the ohmic losses, respectively, in the iris and short sections of the three-section cavity, and in the beryllium copper, magic tee, middle section of the composite cavity. A and B are frequency-dependent geometric constants which can be considered normalized to the fields incident at the face of the cavity's iris. By combining Eqs. A-21, -22, and -23, it is possible to get

$$\frac{(U_o)_{BC}}{B} = (R_s)_{BC} \left[\frac{(Q_o)_{is} (Q_o)_{BC} (Q_e)_{BC}}{(Q_o)_{is} (Q_e)_{BC} - (Q_o)_{BC} (Q_e)_{is}} \right] \quad . \quad (A-24)$$

C. The magic tee with the unknown electroplated coating can now be substituted for the unplated beryllium copper magic tee and the unloaded and single loaded Q's of this three-section cavity are measured, $(Q_o)_x$ and $(Q_L)_x$ respectively. The unloaded Q for this magic tee with the unknown coating can also be expressed as

$$(Q_o)_x = \frac{(U_o)_x}{A(R_s)_{is} + B(R_s)_x} = \frac{(U_o)_{BC}}{A(R_s)_{is} + B(R_s)_x} \quad . \quad (A-25)$$

This equation can be derived from Eq. A-23 because 1) the same iris and short are used for both measurements, hence $A(R_s)_{is}$ remains identical; 2) the geometry of both magic tees is identical, within tolerance, hence B remains the same; and 3) the fields have not changed, therefore $(U_o)_{BC}$ is equal to $(U_o)_x$. Rearranging Eq. A-25 by making use of Eq. A-21 and A-22, results in

$$\frac{1}{(Q_o)_x} = \frac{A(R_s)_{is}}{(U_o)_{BC}} \left[\frac{(Q_e)_{is} (U_o)_{BC}}{(Q_e)_{BC} (U_o)_{is}} \right] + \frac{B}{(U_o)_{BC}} (R_s)_x$$

or

$$\frac{1}{(Q_o)_x} = \frac{(Q_e)_{is}}{(Q_e)_{BC} (Q_o)_{is}} + \frac{B}{(U_o)_{BC}} (R_s)_x \quad . \quad (A-25a)$$

Now substituting Eq. A-24 into A-25 yields the expression for the unknown resistivity of the electroplated magic tee in terms of quantities that are measurable.

$$(R_s)_x = (R_s)_{BC} \left\{ \frac{\left[\frac{(Q_o)_{is} (Q_e)_{BC}}{(Q_e)_{is} (Q_o)_x} \right] - 1}{\left[\frac{(Q_o)_{is} (Q_e)_{BC}}{(Q_e)_{is} (Q_o)_{BC}} \right] - 1} \right\} \quad (A-26)$$

This can be further simplified and finally normalized to pure copper as in Eq. A-17 thusly:

$$(r_s)_x = (r_s)_{BC} \frac{(Q_L)_{BC} (1 + \sigma_{BC}) - \sigma_{is} (Q_o)_x}{(Q_o)_x (\sigma_{BC} - \sigma_{is})} \quad , \quad (A-27)$$

where σ_{is} and σ_{BC} are the VSWR's at resonance of the iris-short cavity and the unplated beryllium copper magic tee cavity, respectively.

APPENDIX III

ERROR ANALYSIS OF THE MAGIC TEE

The description of the circuit operation of the Q meter in Appendix I maintains that the two positions of the short circuit, differing by a quarter of a guide wavelength, can be used to measure the VSWR of the unknown cavity on resonance. The logarithmic difference of the output powers at the E-plane arm of the magic tee for these two positions is said to be

$$20 \log (V_{D_1}) - 20 \log (V_{D_2}) = 20 \log (\text{VSWR})_{\text{cavity}}, \quad (\text{A-28})$$

where V_{D_1} and V_{D_2} are the output voltages to the crystal detector for the two positions of the short circuit which differ by a quarter guide wavelength. It is possible to show that Eq. A-28 is indeed valid if the output voltages to the detector are calculated for the two positions of the short circuit. Figure A-6 shows a complete signal flow graph representation of the magic tee which can be solved for the ratio of the voltage into the detector, V_D , to the input generator voltage, V_G .

The flow graph is a graphical representation of the path of the incident generator voltage wave through the magic tee junction. Once the flow graph has been determined, it can be solved as it stands by using Mason's reduction theorem.⁽¹⁸⁻²⁰⁾ However, the possibility for error and much calculation can be reduced if the flow graph is simplified through the use of geometric and topological rules. A good understanding of these rules can be obtained in a short time from Kuhn's⁽²¹⁾ article on flow graph reduction.

One advantage of simplifying the flow graph is that certain branches and combinations of branches can be eliminated from the graph at the start when a particular problem shows them to have little effect.

In this case of the magic tee, the cross-coupling terms can be eliminated as well as combinations of the generator and detector reflection coefficients, since they can be adjusted to be less than 0.05 in magnitude. The total error involved by doing that is approximately 5 percent in the measurement of the

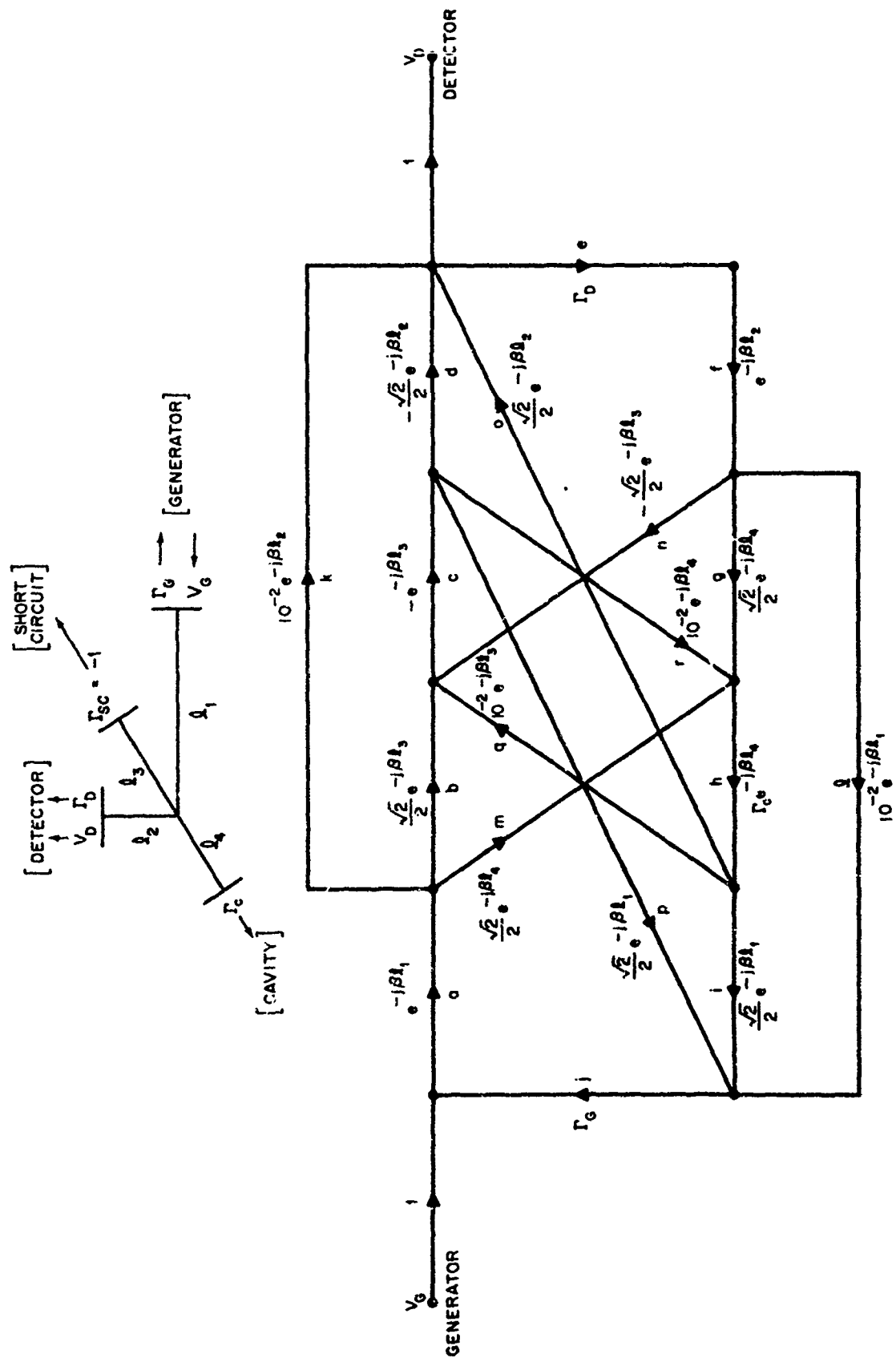


Fig. A-6 Symbolic and signal flow graph representations of the magic-tee hybrid junction.

cavity VSWR. However, the VSWR affects the unloaded Q according to Eq. A-1, and therefore this 5 percent error results in only a one-percent error in Q_0 , which is quite acceptable.

With these simplifications the flow graph can be redrawn as in Fig. A-7a. Splitting a few nodes and rerouting a few branches gives Fig. A-7b and -7c. In Fig. A-7d, branches (mhij) and (efhg) have been eliminated because they contain combinations of the reflection coefficients, Γ_G , Γ_D , and Γ_C , which will be negligible. The splitting of the node between branches (bc) and (d) results in the two self-loops of Fig. A-7e, which can be eliminated by using Kuhn's Rule III, as in Fig. A-7f. Equation A-29 shows the final result for the voltage transfer coefficient between the generator and the detector.

$$\frac{V_D}{V_G} \cong \frac{\frac{1}{2} e^{-j\beta(l_1+l_2+2l_3)} + \frac{1}{2} \Gamma_C e^{-j\beta(l_1+l_2+2l_4)}}{1 + \frac{1}{2} \Gamma_G e^{-j\beta(2l_1+2l_3)} + \frac{1}{2} \Gamma_D e^{-j\beta(2l_2+2l_3)}} \quad (A-29)$$

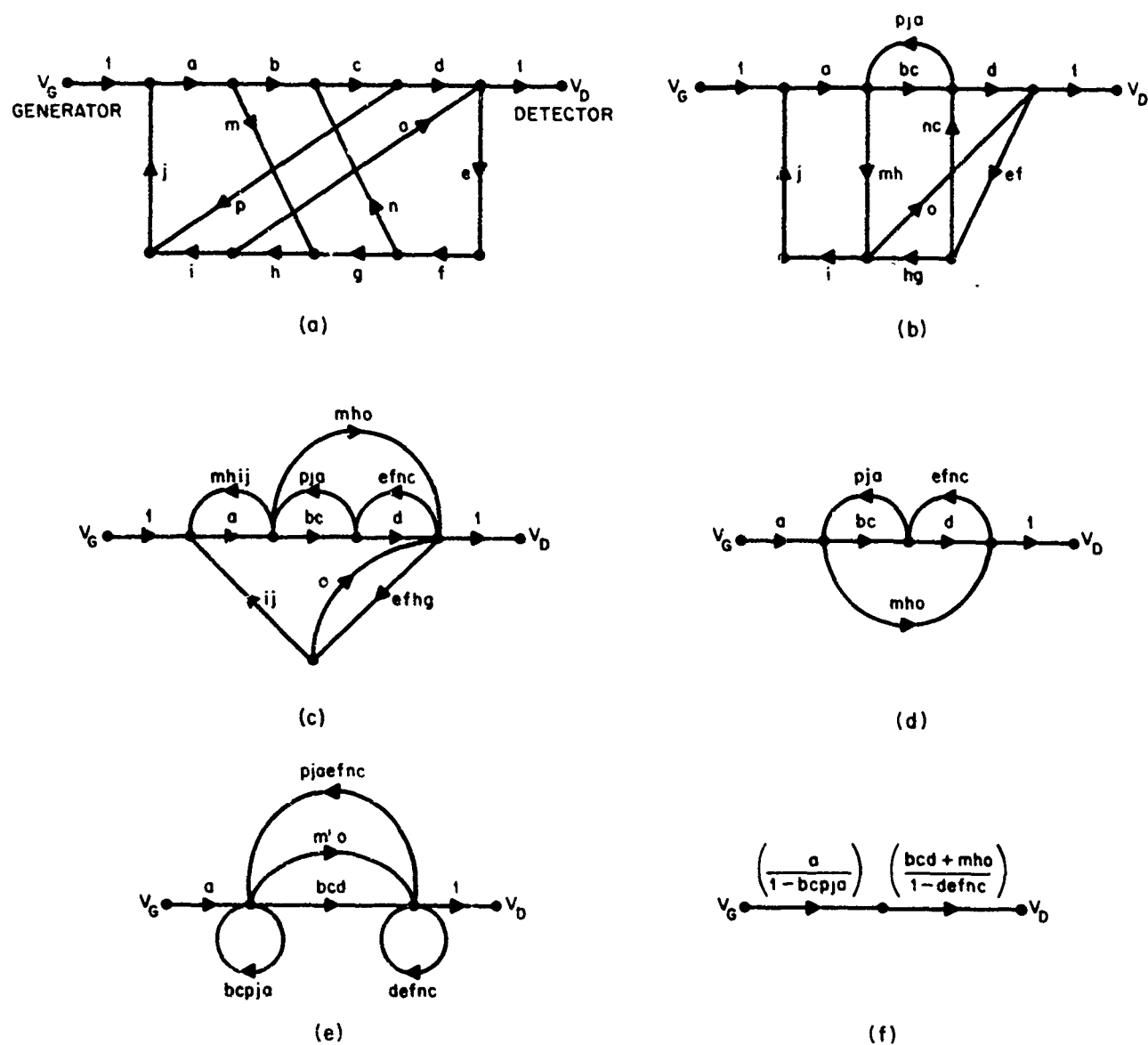
If the two conditions for the short circuit positions are substituted into Eq. A-29, their ratio becomes

$$\text{Case 1: } l_4 = l_3$$

$$\text{Case 2: } l_4 = l_3 + \frac{1}{4} \lambda_{g_0}$$

$$\frac{V_{D1}}{V_{D2}} \cong \frac{1 + \Gamma_C}{1 - \Gamma_C} = (\text{VSWR})_{\text{cavity}} \quad (A-30)$$

The largest error in the Q_0 measurement comes from the visual setting of the bandwidth frequency markers. This may be as much as 3 or 4 percent, bringing the total error in the unloaded Q measurement to 4 or 5 percent. Repeatability of the frequency marker settings for the bandwidth measurement is often a function of the operator and in this case was less than one percent.



$$\frac{V_D}{V_G} \cong \frac{abcd + amho}{1 - bcpja - defnc} = \frac{\frac{1}{2} e^{-j\beta(l_1 + l_2 + 2l_3)} + \frac{1}{2} \Gamma_c e^{-j\beta(l_1 + l_2 + 2l_4)}}{1 + \frac{1}{2} \Gamma_G e^{-j\beta(2l_1 + 2l_3)} + \frac{1}{2} \Gamma_D e^{-j\beta(2l_2 + 2l_3)}}$$

Fig. A-7 Simplification of the magic-tee flow graph.

ACKNOWLEDGMENTS

The author would like to thank Edward Murphy for his helpful comments concerning the chemical aspects of this study and for providing the sample protective coatings which were of paramount importance to this work. The author would also like to thank Elmer Stephens for his work assisting with the fabrication of many of the electroformed waveguide test sections, William Bausha, who measured many of these samples and test pieces on the Q meter, and Adrian A. Browne, who offered many useful suggestions and comments.

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DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) Lincoln Laboratory, M.I.T.		2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None
3. REPORT TITLE Some Practical Considerations for Reducing the Surface Resistivity of X-Band Components		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Technical Note		
5. AUTHOR(S) (Last name, first name, initial) Kessler, Alan H.		
6. REPORT DATE 11 August 1965 (Revised 13 June 1966)	7a. TOTAL NO. OF PAGES 62	7b. NO. OF REFS 31
8a. CONTRACT OR GRANT NO. AF 19 (628)-5167 b. PROJECT NO. 649L c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Note 1965-41 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) ESD-TR-66-242	
10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited.		
11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Air Force Systems Command, USAF	
13. ABSTRACT In a recent experimental study program involving X-band waveguide components, various factors affecting RF resistivity were investigated. Specific results of this investigation included: (1) the successful reduction of the RF resistivity of conventional beryllium copper castings by electroplating with higher conductivity metals, (2) decreasing RF resistivity by lowering surface roughness, (3) the attainment of microwave components cast from a higher conductivity casting alloy than beryllium copper, (4) lowering of the RF resistivity by minimizing the effects of surface oxides and sub-surface contaminants, (5) the use of OFHC and electroformed copper components to achieve low RF resistivity, and (6) an evaluation and comparison of dielectric and metallic protective coatings which inhibit the deterioration of waveguide surfaces.		
14. KEY WORDS waveguide surfaces electroplating microwaves X-band conductivity resistivity		