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Publication Date
1955-04-11

UCRL 2946
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UNIVERSITY OF CALIFORNIA

Ernest O. Lawrence Radiation Laboratory

BERKELEY, CALIFORNIA

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UNIVERSITY OF CALIFORNIA
Radiation Laboratory
Berkeley, California
Contract No. W-7405-eng-48

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Printed for the U. S. Atomic Energy Commission

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Summary

The eddy-current bridge described in this paper was the outgrowth of quality-control research on copper-plated surfaces to be used in a radiofrequency resonator. A test for skin loss at the operating frequency was necessary, but the standard method of incorporating individual samples in a suitable test resonator for loss measurement would have been prohibitively time-consuming. A review of the approximate quantities involved in a direct surface measurement of loss indicated that a practical measuring instrument could be made.

The principle of the eddy-current bridge is to excite eddy currents in the sample surface by induction from an energized loop, and to couple out a signal proportional to loss from a second loop in close proximity to the surface. The two loops are held in a fixed relation to each other in an assembly termed the instrument head, which is placed upon the sample surface. Resistive and reactive balancing operations are then performed to obtain the skin loss. Different regions of a large sample may be successively tested, or many different samples measured, at the rate of several a minute. A frequency range of 1 kc to 100 Mc has been explored with the present instrument, and some typical loss figures for metals are tabulated. Directional conductivity effects of a few percent have been measured in machined surfaces.

Introduction

It is often of interest to designers of large rf resonant systems to have a measurement of the conductor skin resistance. For resonators fabricated of materials of known composition--e. g., sheet copper--estimates of skin loss are straightforward. There are cases, however, for which no handbook figures of resistivity are available. For example, the resonator may be fabricated of steel for structural support, with a layer of copper applied subsequently by vacuum evaporation, spraying, or electroplating. In any of these processes, the resistance of the resultant copper layer is variable for several reasons. Some obvious factors are roughness of the base metal; thickness, purity, and structure of the copper layer; and the surface treatment such as polishing, buffing, or etching. In each case, the rf property of importance is the conductivity of the thin surface layer in which current flows. In general the conductivity must be measured at the frequency of interest rather than by extrapolation, since the properties may vary considerably with depth. The eddy-current bridge was designed to measure the conductivity of sample surfaces at an operating frequency, the end in view being the production of low-loss surfaces. A sample of oxygen-free high-conductivity copper (OFHC) was used as a standard. Although most of the original work was done with copper, the bridge is not restricted to materials of high conductivity. In fact, once the problem has been solved for good conductors, the measuring technique is simple for lossy materials such as graphite.

Conductor Surface Parameters

An appreciation of the magnitudes involved in measuring skin loss can be gained by reviewing the following approximate table for copper. Surface resistance and skin-depth values given are calculated from the standard formulas.

Table I

Material	Frequency	Skin Depth (mils)	Surface Resistance ($\mu\Omega$/square)
Copper	700 cps	100	7
"	70 kc	10	70
"	7 Mc	1	700
"	700 Mc	0.1	7,000

Surface resistance is the parameter to be measured. The general method is to produce a surface current of the order of a few amperes per unit width and to measure the resulting IR drop across a few unit lengths. Required current in the driving loop is then several amperes, and the loss signal measured in the pickup loop is of the order of millivolts, for copper at 10 Mc. Signals in the pickup loop are directly proportional to surface loss of the sample for the idealized case of a pickup loop buried in the surface.

Principle of Operation

Eddy currents are induced in the sample surface by passing a current of the desired frequency through the driving loop positioned a radius above and parallel to the surface. The driving loop is a single turn, electrostatically shielded. A pickup loop coaxial with the driving loop lies on the surface, separated by 0.005-inch mica insulation to hold the geometry constant.

Since the pickup loop is not physically buried within the surface, there is a signal-voltage component corresponding to flux leakage under the pickup loop itself. This is in quadrature with the desired voltage, since the leakage signal represents a reactive component, while the loss signal of course corresponds to a real power loss. The method of obtaining a signal proportional to loss is to buck out the leakage signal with a voltage derived from a small adjustable loop close to the driving loop. Setting the adjustable loop for a minimum total signal corresponds to a reactive balancing operation.

At reactive balance, the ratio of loss signal to surface current is proportional to surface resistance. If a fixed geometry is maintained between driving coil and surface, driving-loop current suffices as a measure of surface or eddy current.

This fortunate property of the system stems from the very poor impedance match between the conductor surface and space. That is, the samples are better than 99% reflectors of energy over the frequency range 0 to 100 Mc. Good accuracy is obtained with surface resistances even as high as those of graphite. For materials whose surface resistance is an appreciable fraction of 377 ohms/square, surface current is correspondingly less than that for a nearly perfect reflector. Since calibration has been done, as a rule, by the substitution of known samples, the error for any conductor measured is small.

Circuitry I

A circuit based on these principles is shown in Fig. 1. The electrostatically shielded driving loop forms a termination for the driving line. A 5687 drives the system at its resonant frequency, adjusted by cable patching. Loop current is 5 amperes. The ac plate supply produces half-sine-wave bursts of rf. A crystal diode rectifies the stepped-up loss signal, which then appears on the scope adjacent to the oscillator pulse from the 6AL5. Adjustment of the Helipot dial to equalize the heights of loss pulse and oscillator pulse corresponds to a resistive balancing operation. The Helipot setting is recorded as the relative surface resistance of the sample.

Good shielding is essential between the driving and the pickup circuits, since the pickup voltage is perhaps five orders of magnitude less than the oscillator voltage. For runs greater than a few feet, doubly shielded coaxial cable is advantageous. Vibration of the head produces a varying reactive unbalance, hence rigid construction of the instrument head is essential.

The crystal diode, although it introduces appreciable nonlinearity into the circuit, is used here because of its simplicity. With this note, Table II is presented. All the data shown were taken with the circuit of Fig. 1. The samples were not cleaned to remove surface films but are in "as received" condition with the exception of the OFHC copper standard.

Instrument Heads

Figure 2 shows the circular loop head described, and also a linear head design. In each case, the driving line is electrostatically shielded. On the circular model, the bucking-loop adjustment handle is visible. The linear model has the equivalent of a fixed bucking loop, and a vernier adjustment is provided remotely. An O-ring seals the linear head to the test surface so that atmospheric pressure may be used to hold it firmly in position. The valve and vacuum connection may be noted extending parallel to the signal lines.

Dimensions are chosen on the bases of area to be scanned, and of maximum frequency. The models shown have active diameter and length respectively of 0.75 inch, and perform well from audiofrequencies to 100 Mc. Upper frequency limits occur where the loop dimensions approach a quarter wave length.

Table II

rf Resistance of Various Materials

Sample		Relative loss at 12 Mc	Relative loss at 40 Mc
Aluminum	2S	1.3	1.5
Alloy	24S	3.0	2.2
Alloy	61S	1.9	1.8
Brass		2.1	2.5
Copper	Soft	1.0	1.0
	Hard	1.0	1.0
	OFHC	1.0	1.0
	Phosphorus-deoxidized	1.3	1.3
	Beryllium copper	4.2	3.6
	Phosphor bronze	4.8	4.4
Graphite		63.0	58.0
Lead		7.2	6.1
Manganin		11.0	9.5
Molybdenum		2.7	2.3
Solder (Soft)		6.4	5.6
Iron	Mild steel	74.0	71.0
	Auto-body	85.0	65.0
	Inconel	19.2	16.5
	S. S. 302	8	14.7
Silver	(99.7% pure)	1.1	1.1
	Plating	1.0	1.0
Zinc	Plated chassis	27.4	2.8
	Galvanized iron	4.4	2.7
Chromium	Plating (UCRL)	11.0	
Tungsten		2.7	2.3

Typical Test on Copper-Clad Steel

Figure 3 shows some prepared surfaces of copper-clad steel, 0.050-inch OFHC copper on ASTM-A-212 steel 0.450 inch thick. Initial testing showed the stock surface 1.4 times the standard loss. Machining operations, evident in the upper set of samples, were carried out in 0.001-inch steps. All the samples with 0.003 inch or more stock removal show conductivity within a few percent of the standard. The center row of samples has been etched with 10% ferric chloride solution for varying periods. Again, about 0.003 inch of copper must be removed to obtain a good conductivity at 40 Mc, the test frequency. The optical appearance of the samples is quite unreliable as an indicator of quality in this case. Samples in the bottom row have been treated with nitric acid, sandblasted, and dipped in aqua regia. Any of the methods of surface-layer removal is satisfactory, but sandblasting results in a more lossy surface, presumably from increased surface roughness.

Ferric chloride etching following steam cleaning has been adopted as the method of treating the copper and gives a surface with about 99% the conductivity of machined OFHC copper, and an average roughness of 63 to 125 microinches.

Manganin-Standard Bridge

Circuitry II

Figure 4 is a schematic diagram of an eddy-current bridge using a manganin standard for resistance comparison. Two similar linear heads are used, one for the sample and another, internal to the bridge, operating on the manganin. Rotation of the internal pickup loop provides a resistive balance, the dial reading indicating loss relative to manganin. For samples more lossy than manganin, attenuation can be switched into the loss signal from the sample head. Although the major reactive balance is built into the sample head by proper geometry, a vernier adjustment is provided locally.

The stability is such that 5° temperature variations in the sample can be followed. Linear head design permits reading loss along various directions. A particular set of samples of 0.003-inch copper plating on steel showed a loss 3% to 5% higher across grain than along grain. The grain reproduced in the plating was a regular set of parallel furrows produced in a planing operation.

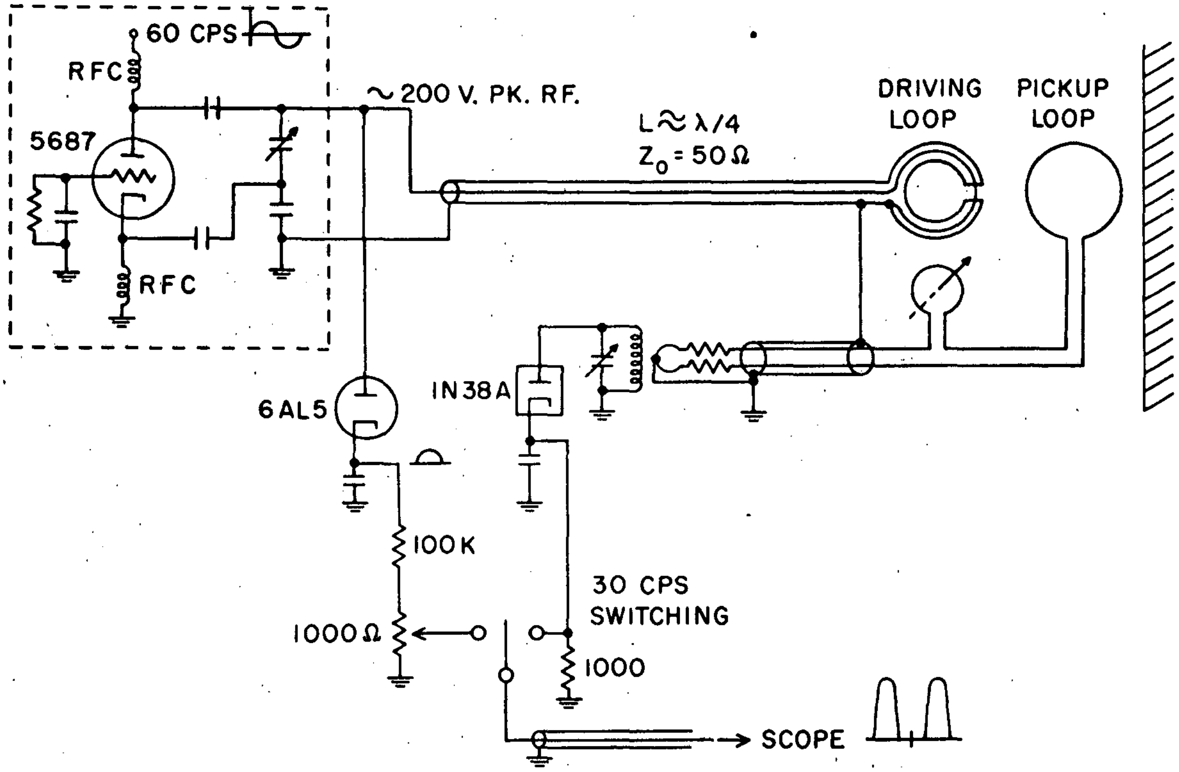

Fig. 1 Circuit diagram of original skin resistance meter.

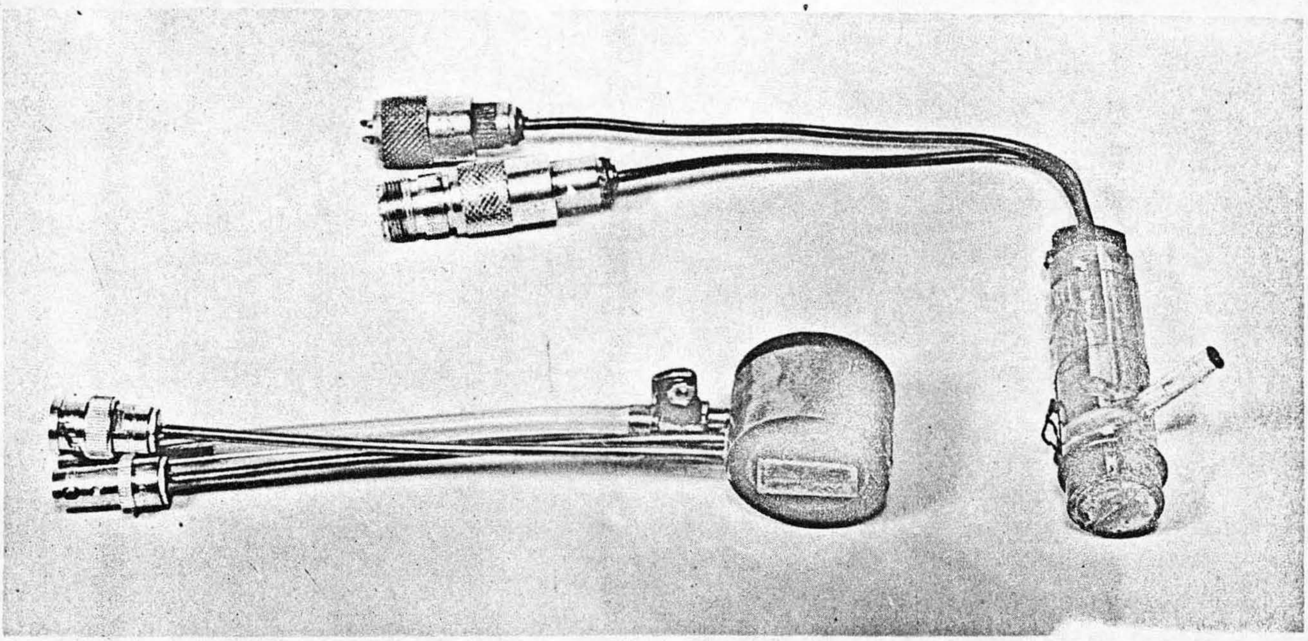

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Fig. 2 Linear and circular instrument heads.

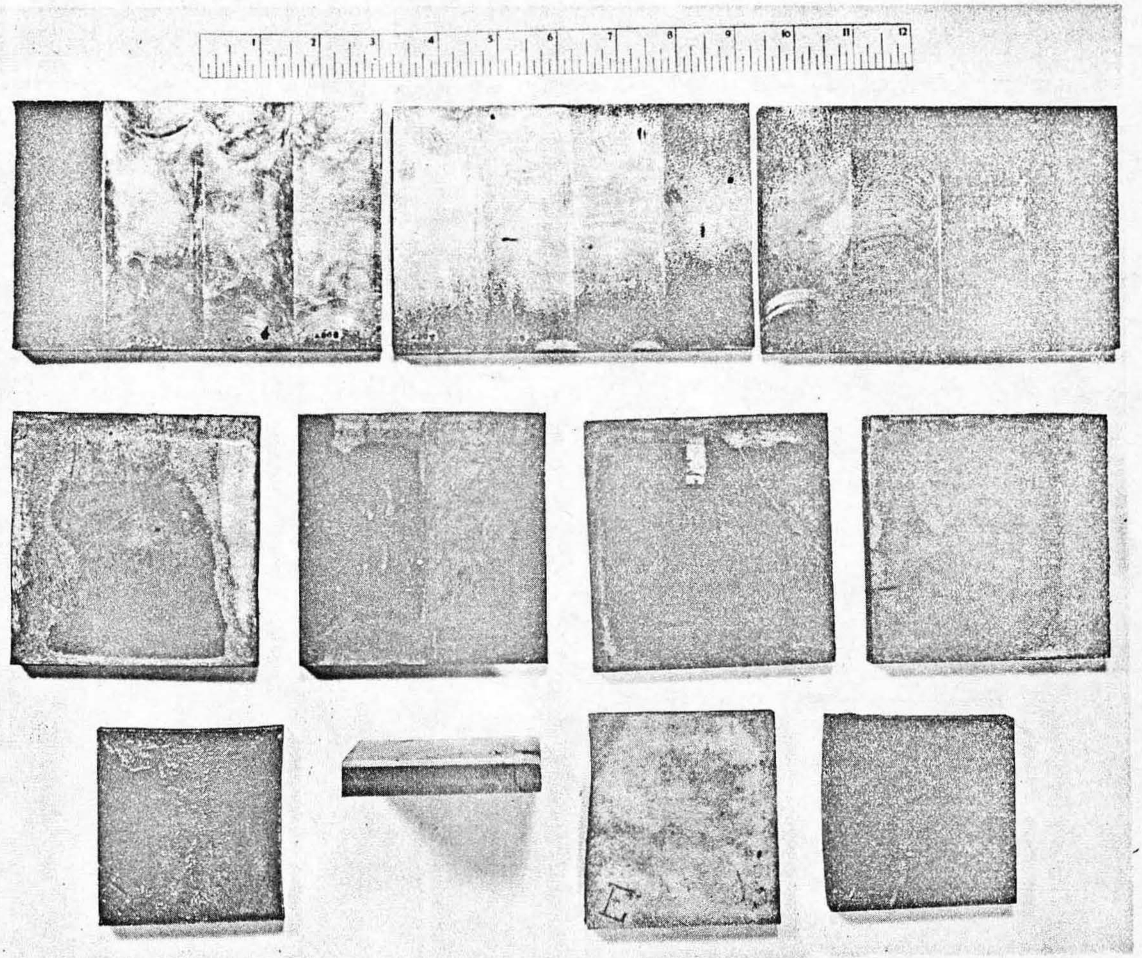

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Fig. 3 Copper-clad steel samples.

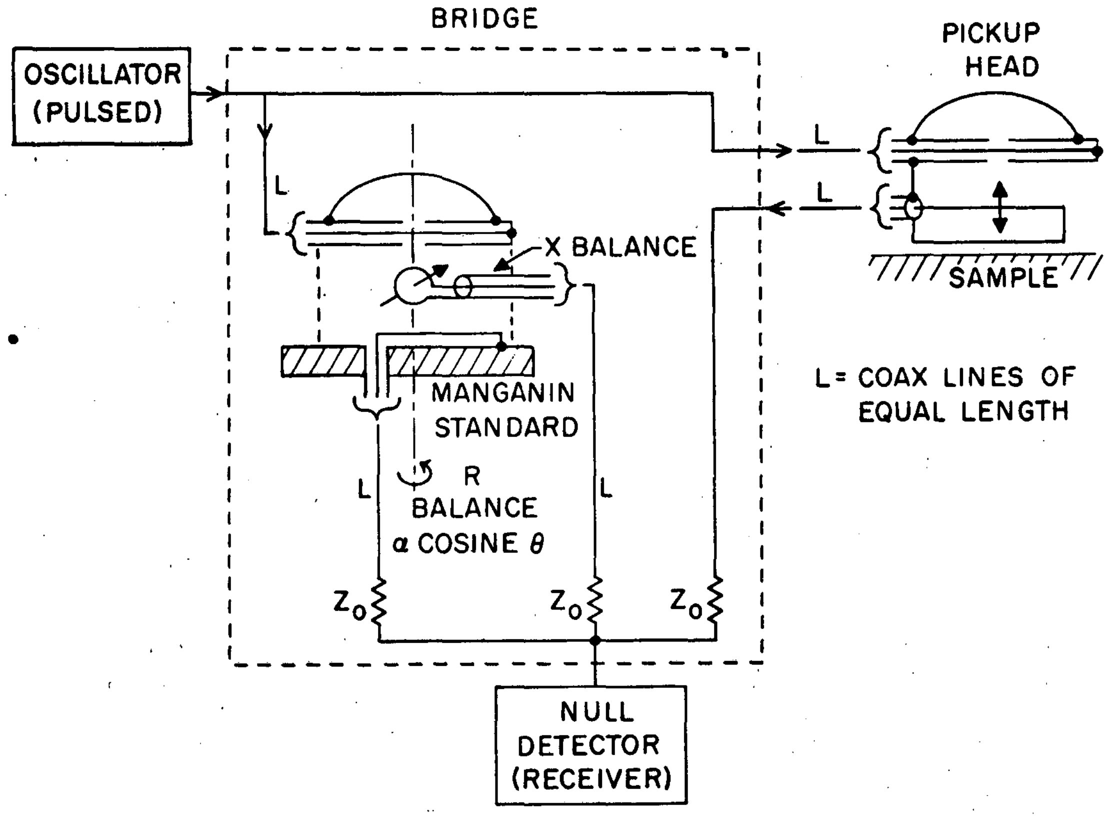

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Fig. 4 Manganin standard eddy-current bridge.