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LB-872

BALANCE MEASUREMENTS ON BALUN TRANSFORMERS

RADIO CORPORATION OF AMERICA

RCA LABORATORIES DIVISION

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Balance Measurements on Balun Transformers

Approved

Stuart W. Seeley

ERRATA

I. LB-905, *Power Junction Transistors by the Alloy Process.* In Fig. 4, p. 7, the curve labels $V_c = 10_v$ should read $V_c = 3_v$. The labels *p-n-p* and *n-p-n* should be interchanged.

II. LB-872, *Balance Measurements on Balun Transformers.* In Fig. 8, p. 8, the following changes and addition should be made:

1. In detail 12, make *.120 DIA* read *.139 DIA.*
2. In detail 13, make *.139 DIA* read *.120 DIA.*
3. In detail 7, draw *.875 DIA* center hole as in detail 5.

Balance Measurements on Balun Transformers

Introduction

This bulletin discusses means of establishing a figure of merit which expresses the relative quality of balance obtained from balun transformers. This figure of merit, termed the balance efficiency, is defined and expressed in terms of measurable quantities. A balance comparator to measure the balance efficiency of baluns is described, and tests on representative baluns are presented.

General Discussion

Standard antenna systems used in television reception of horizontally-polarized signals are of the balanced, symmetrical type. Modern receivers are almost exclusively designed with unsymmetrical, coaxial inputs because of economic and engineering advantages. Therefore an isolation transformer is required to join the two systems without disturbing their inherent properties.

In past practice, geometrically unsymmetrical systems such as coaxial lines and single-ended loads have been termed as unbalanced systems. Hence the isolation transformer has commonly been called a balun as an abbreviation for balance-to-unbalance transformer.

To avoid confusion and conform with common usage, it is important to note that the terms "balanced" and "unbalanced" are applied in two different manners. Where used in connection with a transmission line or load, reference is made to the physical symmetry of the line construction or the equality of the load terminal impedances to ground. The terms are also used, however, to denote the type of excitation or mode of operation.

A symmetrical system can support simultaneously two transverse electromagnetic (TEM) modes of propagation. The balanced or push-pull mode is obtained where the currents on symmetrically located conductors are equal in magnitude and opposite in phase at all cross sections. This is the normal operating condition of non-radiating open-wire transmission lines and shielded-pair transmission lines with zero net current flow on the inside of the shield. Conversely, equal in-phase currents on the symmetrically located conductors are defined as the unbalanced or push-push mode. Here the potential difference between the conductors is zero at all cross sections. An open-wire transmission line acting as an antenna against ground is an example of unbalanced mode operation. Another example is the shielded-pair line functioning as a coaxial cable with the pair of conductors effectively joined together and return currents flowing on the inside of the shield.

The normal directional and electrical characteristics of the symmetrical receiving antenna system are based on balanced mode design. An unbalanced load termination permits the existence of undesired push-push currents,[1] resulting in extraneous signal pickup by the transmission line and a reduction in gain and signal-to-noise ratio.

The function of the balun is to transfer efficiently the balanced mode energy from the antenna and to prevent unbalanced mode currents

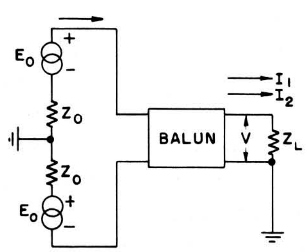
[1] K. Tomiyasu, "Unbalanced Terminations on a Shielded-Pair Line", *Journal of Applied Physics*, p. 552, June, 1950.

from coupling to the receiver input. Frankel[2] has given a general equivalent circuit and necessary requirements for a perfect balun and shows the independence of its operation on source or load impedances.

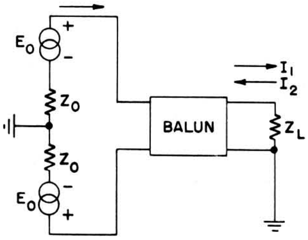
Some baluns, however, have balance characteristics which are a function of frequency as well as the driving conditions. Since practical installations vary widely in the type of receiving antennas used and the layout of the transmission line in relation to the field configuration in the vicinity, it is obviously impossible to measure the balance quality of a balun for all operating conditions. Therefore, an arbitrary standard setup is presented in this bulletin for comparing the relative balance merits of different baluns. A simple device called the balance comparator is described for obtaining the balance efficiency of baluns.

Theory

Fig. 1a shows the block diagram of a balun joining a balanced mode generator, having an internal impedance of $2Z_o$, to an unbalanced load, Z_L, represented by the television receiver



(a) - With a balanced mode generator



(b) - With an unbalanced mode generator.

Fig. 1 - Block diagram of balun feeding an unbalanced load.

[2]S. Frankel, "Reactance Networks for Coupling Between Unbalanced and Balanced Circuits", *Proc. I.R.E.*, p. 486, Sept. 1941.

input. The balun is assumed to be made of linear, passive, reactive elements. All expressions are complex quantities.

The load current components, I_1 and I_2, result from applying each of the voltages, E_o, separately. Hence, with both voltages applied, the total load current is (I_1+I_2) by the principle of superposition.

Now if one of the input voltages is reversed in phase as in Fig. 1b, an unbalanced mode generator is obtained, and the load current becomes (I_1-I_2). If the balun input is balanced, this unbalanced mode is suppressed and I_1 equals I_2.

If the balun input is unbalanced, the ratio R of the receiver input currents (or voltages) for the two types of balun input feed is a measure of the balance quality.

Or $$R = \left|\frac{I_1 - I_2}{I_1 + I_2}\right| = \left|\frac{1-(I_2/I_1)}{1+(I_2/I_1)}\right| \qquad (1)$$

It is logical and desirable, however, that the quality of balance be stated as a percentage with perfect balance expressed as 100 per cent and complete unbalance as 0 per cent. Therefore let the balance efficiency be defined as:

$$\text{balance efficiency} = \frac{100}{1+R} \qquad (2)$$

The relation between the balance efficiency and the impedances of the load and generator is considered next.

Applying Thevenin's theorem to the output circuit,

$$I_1 = \frac{V_1}{Z_L+Z_1} \qquad (3)$$

and

$$I_2 = \frac{V_2}{Z_L+Z_1} \qquad (4)$$

where Z_1 is the impedance measured looking back into the balun output terminals with the input voltages, E_o, turned off, and V_1 and V_2 are the open-circuit output voltages obtained by turning on the input voltages separately.

It is seen that the ratio of I_1 to I_2 is unaffected by the value of the load impedance, Z_L. Therefore, from Eq. (1), the balance efficiency is also independent of the load impedance.

The load current components are proportional, respectively, to the balun input terminal voltages produced by applying the two generators separately. However, since these terminal voltages are dependent upon the generator internal impedance as well as the balun input impedances to ground, then the ratio of I_1 to I_2, and hence the balance efficiency, is a function of the generator internal impedance.

Therefore, for consistent comparison purposes, the balun should be tested with a generator having an internal impedance equal to the nominal value for which the balun was designed to obtain the required impedance transformation. In the usual television practice this value is nominally 300 ohms.

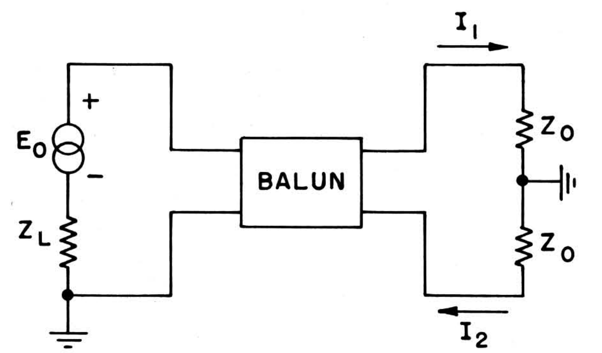


Fig. 2(a) – Block diagram of balun joining an unbalanced mode generator to a balanced load.

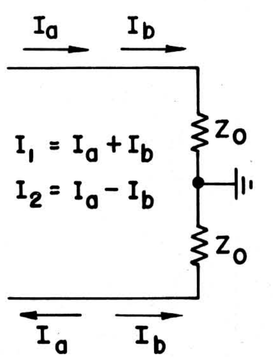


Fig. 2(b) – Resolving the load currents into push-pull and push-push components.

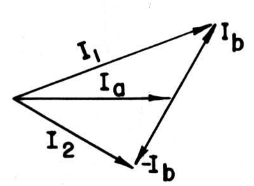


Fig. 2(c) – Vector diagram of the load current components.

If desired, the balun may be used and tested with energy flowing in the opposite direction as shown in Fig. 2a.

Here the balun joins an unbalanced mode generator to a balanced load. Using the reciprocity theorem, the voltages and currents of Fig. 1a are transposed as in Fig. 2a. In the general case, the unequal load currents I_1 and I_2 may be resolved into push-pull components I_a, and push-push components, I_b, as shown in Fig. 2b. Fig. 2c diagrams the vector relationship of the output currents. It is obvious that a simple volt-meter measurement of the output voltages to ground is not sufficient to indicate the balance quality since the relative phase is not taken into account.

Solving for I_b and I_a:

$$I_b = \frac{I_1 - I_2}{2} \tag{5}$$

and

$$I_a = \frac{I_1 + I_2}{2} \tag{6}$$

Therefore

$$\left| \frac{I_b}{I_a} \right| = \left| \frac{I_1 - I_2}{I_1 + I_2} \right| = R \tag{7}$$

Eq. (7) shows that the same ratio R may be obtained as in the previous discussion by measuring the push-push and push-pull components of the output currents. The balanced load impedance in this case must again be equal to the nominal balanced value for which the balun was designed.

The standard procedure thus described for obtaining the balance efficiency is summarized as follows:

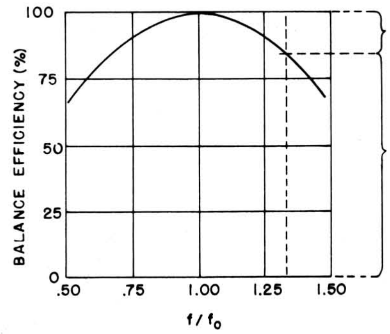
If the balun is used to join a balanced generator to an unbalanced load, the internal impedance of the test generator is made equal to the designed balanced impedance of the test balun. The ratio R of the balun output voltages (or currents) is measured for push-push and push-pull driving voltages as in Figs. 1b and 1a, respectively.

If the balun is used to join an unbalanced generator to a balanced load, the ratio R of the unbalanced and balanced components of the output currents is determined. The balanced load in this case must be equal to the impedance for which the balun was designed.

Having determined the ratio R, the balance efficiency is calculated as in Eq. (2).

A typical example of the balance efficiency plotted against frequency is shown in Fig. 3.

An advantage in expressing the quality of balance in this manner is seen in the above example where the relative absolute magnitudes of the measurements for either type of balun application are apparent at any frequency.



TYPE OF USE	
BALANCE-TO-UNBALANCE	UNBALANCE-TO-BALANCE
$\vert I_1 - I_2 \vert$	$\vert I_b \vert$
$\vert I_1 + I_2 \vert$	$\vert I_a \vert$

Fig. 3 – A typical example of the balance efficiency plotted vs frequency.

It will be noted again that the balance efficiency measured as outlined is not necessarily the same as that obtained in actual practice since a given antenna system may not conform to the described conditions. Nevertheless, this procedure is valuable in affording a means of accurately comparing different baluns. Future field use may establish some practical lower limit of balance efficiency as measured in this manner.

One means of experimentally determining the data required for calculating the balance efficiency is given by Tomiyasu.[1] Another variation is described below.

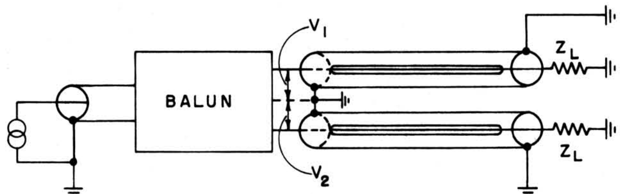


Fig. 4 – Double measuring line method of measuring the balance efficiency.

The balanced output leads of the balun connect to the inner conductors of two slotted coaxial measuring lines as shown in Fig. 4. The characteristic impedance of the two lines is equal to their terminating loads.

As the lines are identical and matched, the relative absolute magnitudes of the output voltages, V_1 and V_2, are found by sampling each line with a probe and receiver.

The phase relationship is measured by the use of two adjustable probes joined by equal length lines to the receiver. The probe depth and position on each of the lines are adjusted for zero receiver indication. Since the phase shift is linear on the two matched lines, the relative phase difference between V_1 and V_2 may be calculated.

Hence, from Eq. (7):

$$R = \left|\frac{I_1 - I_2}{I_1 + I_2}\right| = \left|\frac{V_1 - V_2}{V_1 + V_2}\right| \qquad (8)$$

These methods, however, are cumbersome and require special slotted lines.

The Balance Comparator

The layout of a simpler device to measure the balance efficiency of baluns is drawn in Fig. 5. Two short coaxial lines are positioned at right angles with inner conductors consisting of two small carbon resistors (Z). One end of each resistor is grounded to its respective outer conductor by means of a shorting disc (C). The free ends of the two resistors lead to

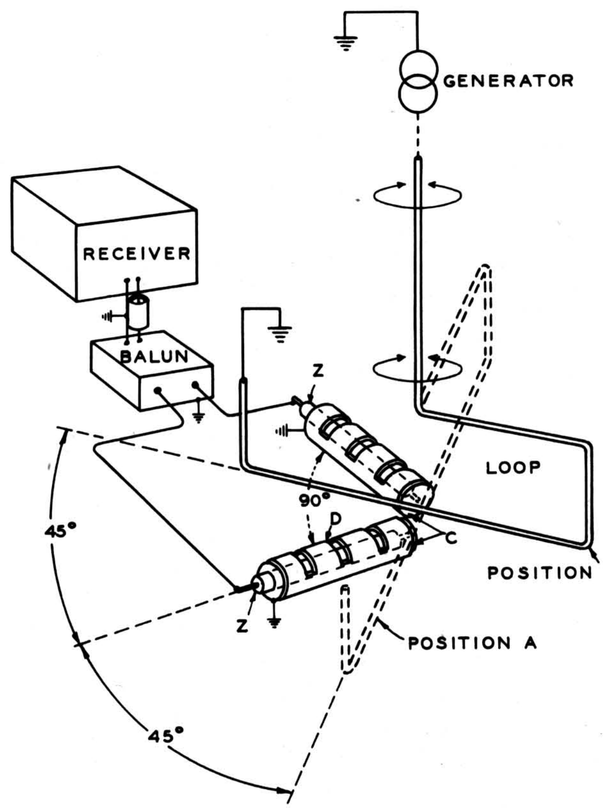


Fig. 5 – Schematic diagram of balance comparator.

the balanced terminals of the balun under test. The outer conductors of the coaxial lines and the balun ground terminal are joined together. The coaxial or unbalanced terminals of the balun connect to a receiver or other indicator.

A generator connects to a single-turn loop that may be rotated on an axis perpendicular to the plane of the two coaxial lines. A number of saw-cuts (D) in each of the coaxial lines provide electrostatic shielding but permit electromagnetic coupling between the loop and resistors. The extension of the resistor axes and the axis of loop rotation intersect in a common point.

With the loop bisecting the right angle formed by the two coaxial lines (position B), equal in-phase voltages are effectively induced in series with the resistors. With the loop rotated 90 degrees to position A, the induced voltages are equal and out-of-phase.

Therefore, the conditions of Figs. 1a and 1b are satisfied if the value of the coaxial resistors, Z, are equal to one-half of the normal operating load of the balun under test.

In operation, the loop is simply rotated to positions B and A, and from the ratio (R) of the corresponding receiver indications, the balance efficiency is calculated by Eq. (2).

As described in the preceding section, identical results will be obtained if the receiver and generator are interchanged.

It is seen that the relative magnitude of the currents I_1 and I_2 of Fig. 2a may also be found by rotating the loop to the 45-degree positions such that it is parallel to each of the resistors, R, of Fig. 5 in turn. Hence the relative phases of the vectors of Fig. 2c may be calculated.

Another application of the device may be in determining the operating characteristics of circuits other than baluns. For example, it might be desired to feed two networks with in-phase or push-push currents only from a common generator. The balance comparator could then be used to determine the extent to which the desired conditions were obtained.

Front and back photographs of the balance comparator are illustrated in Figs. 6 and 7, respectively. Fig. 6 shows the rotating loop housing with the loop coaxial connector. The ungrounded resistor terminals are seen extending from the top of the comparator assembly in the back view of Fig. 7.

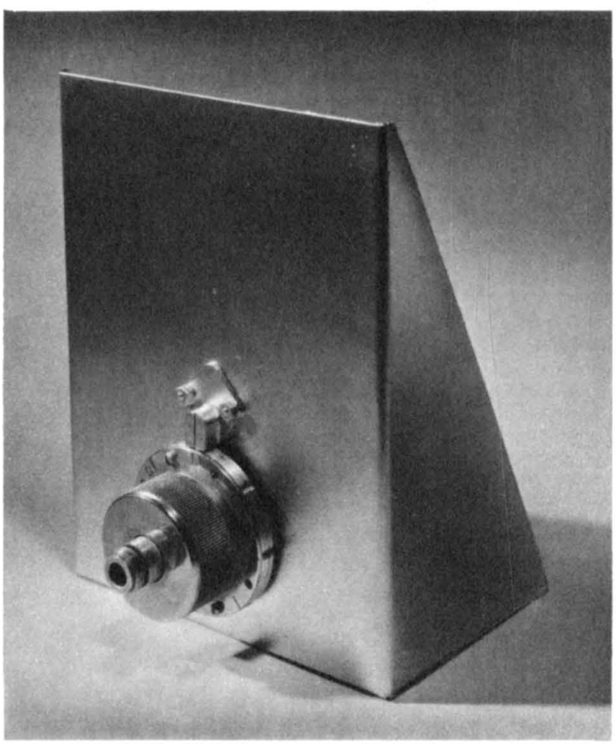


Fig. 6 – Front view of balance comparator.

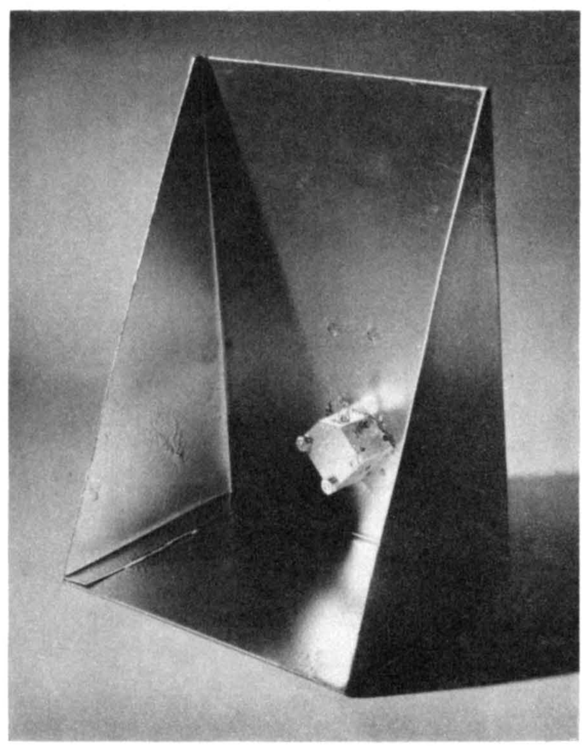


Fig. 7 – Rear view of balance comparator.

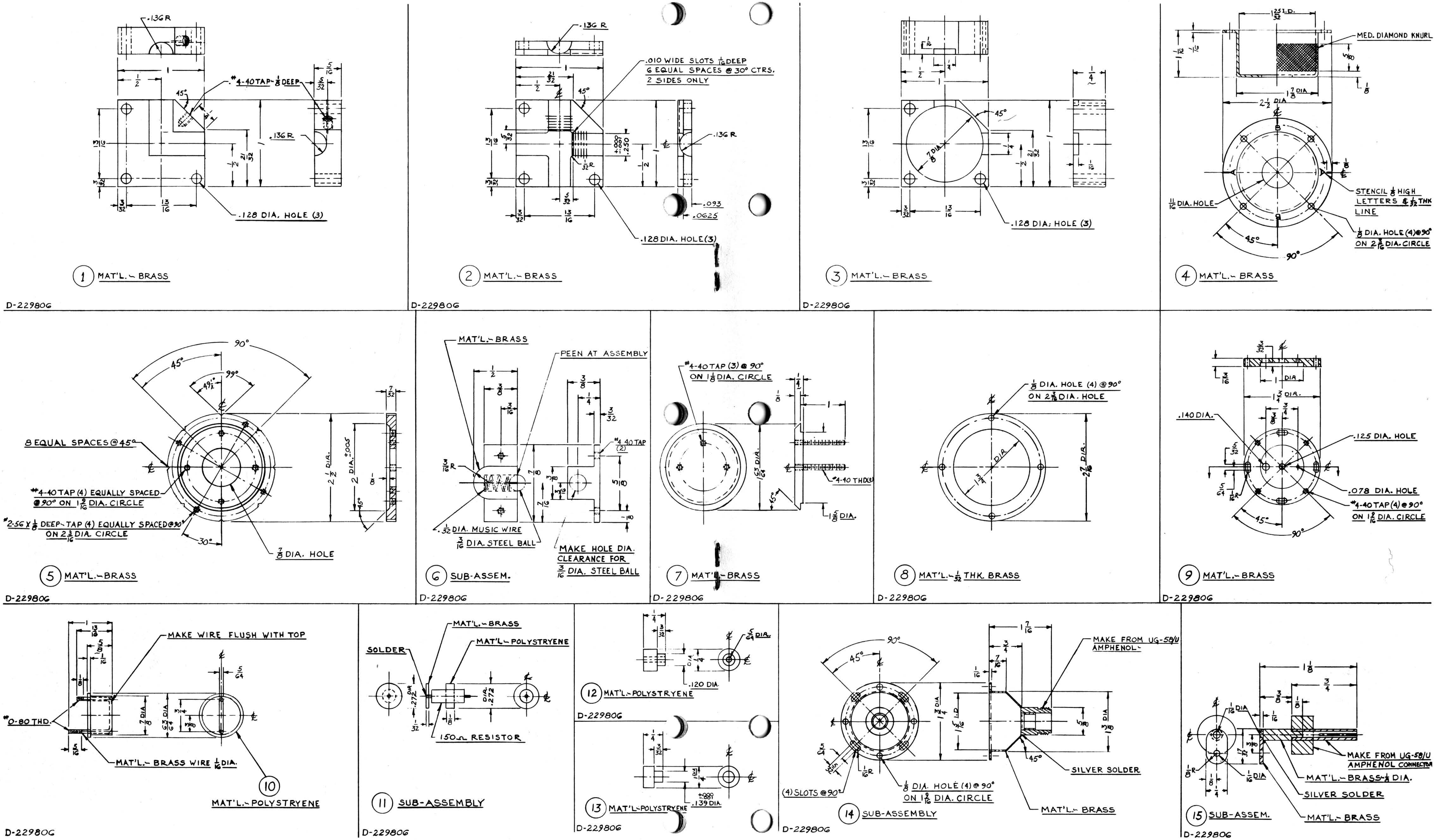


Fig. 8 – Mechanical details of the balance comparator.

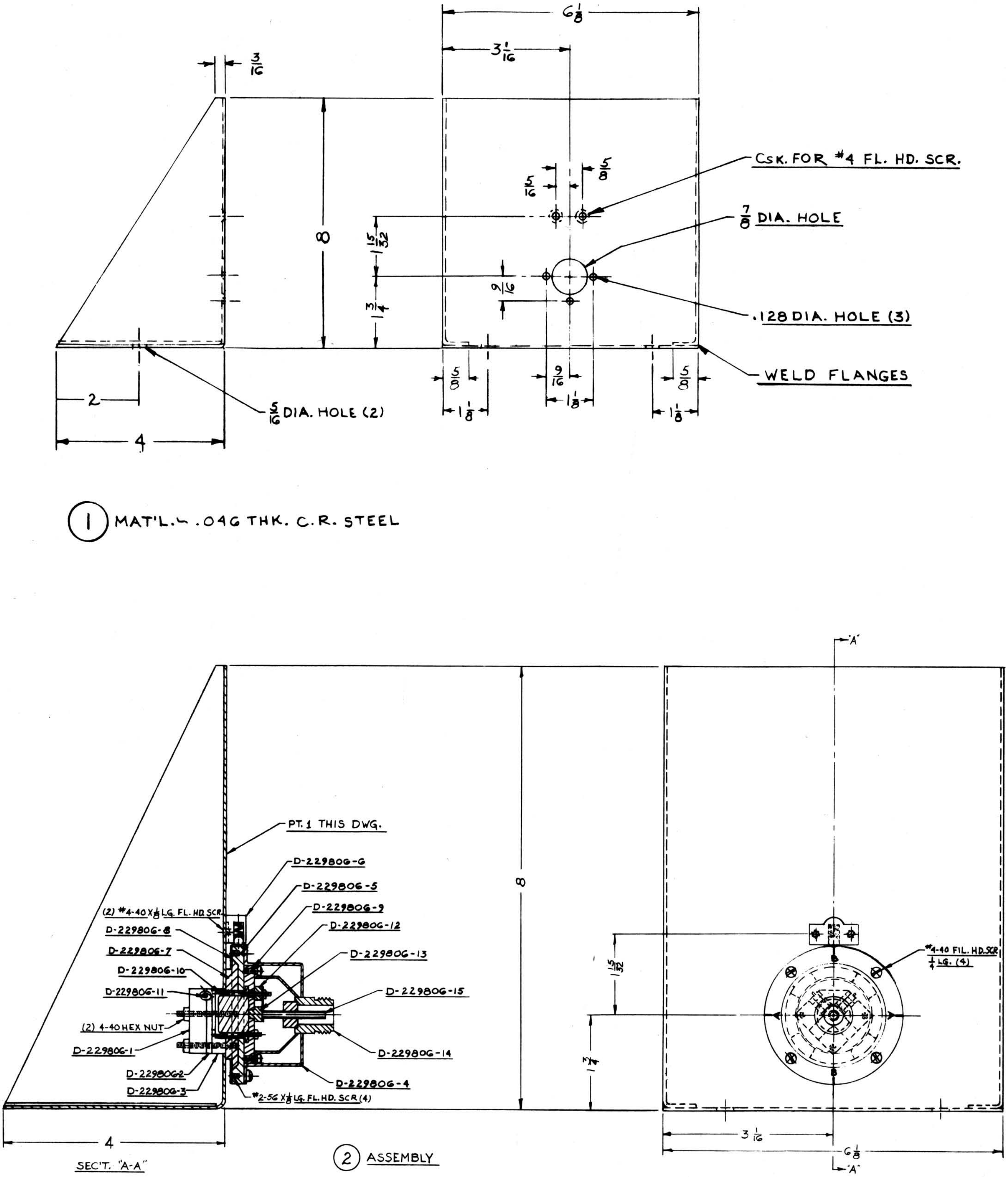


Fig. 9 – Assembly of the balance comparator.

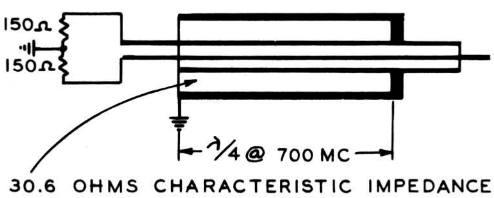
The test balun is mounted on the vertical support plate directly above the resistor terminals. Considerable care must be exercised in maintaining short symmetrical connections between the balun and comparator terminals, especially in the u-h-f band.

As most of the baluns in television use are designed for nominal balanced impedances of 300 ohms, 150-ohm resistors were used in the balance comparator. However, the resistor block assembly is designed so that other values may be easily substituted if necessary.

Mechanical details and assembly of the balance comparator are given in the drawings of Figs. 8 and 9.

Balun Tests

λ/4 SLEEVE BALUN



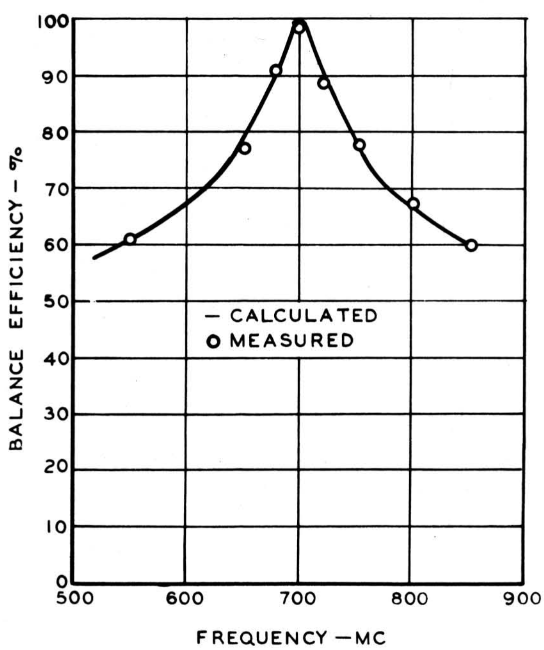
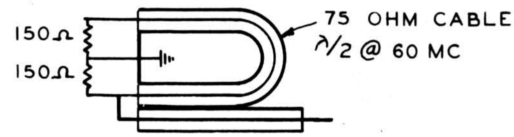


Fig. 10 - Balance efficiency vs frequency of λ/4 sleeve balun.

λ/2 LOOP BALUN



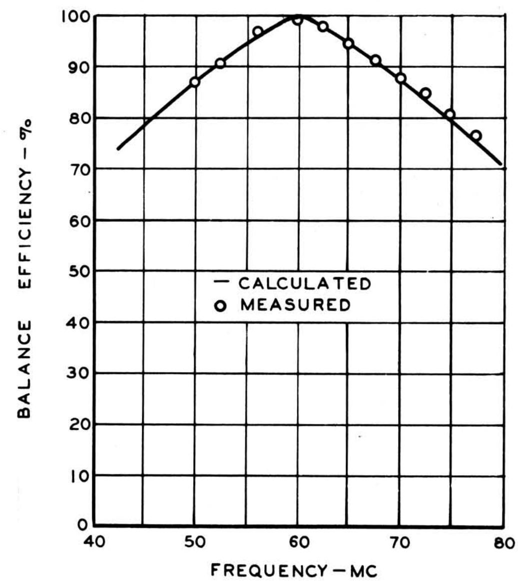
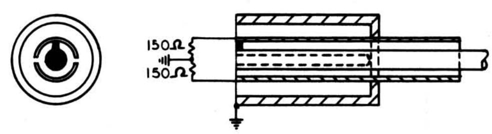


Fig. 11 - Balance efficiency vs frequency of λ/2 loop balun.

SLOTTED BALUN



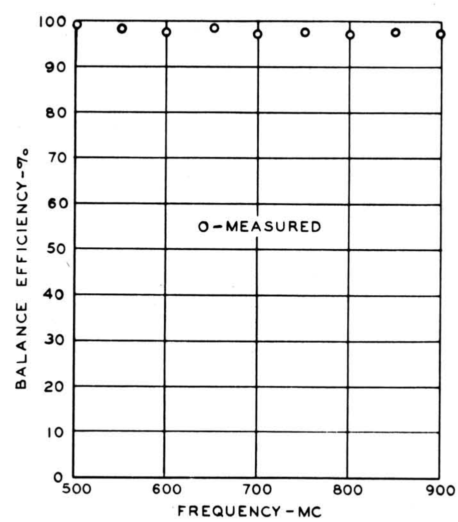


Fig. 12 - Balance efficiency vs frequency of slotted balun.

In order to check the accuracy of the device, measurements were taken on baluns having easily calculated balance efficiency characteristics.

Fig. 10 shows quite close agreement between the calculated (Appendix 1) and measured data obtained in the u-h-f range from a simple balun. This balun is formed by a shorted coaxial sleeve, a quarter-wave in length at the mid-band frequency, which isolates one end of the unbalanced coaxial line from ground potential.

Calculated (Appendix 2) and measured data in the v-h-f range obtained from another commonly used balun are plotted in Fig. 11. This balun is formed from a phase-reversing cable one-half wave in length at mid-band frequency.

The balance characteristics of both types of baluns are seen to be rather sharp in terms of wide-band coverage.

A further check (Fig. 12) was provided by measurements taken on a balun known to be balanced independent of frequency change. This balun consists of two diametrically opposite slots cut in the outer conductor of the unbalanced coaxial line and the inner conductor shorted at the open end to one of the line sections produced by the slot. The slots are one-quarter wave in length at the mid-band frequency for the best impedance characteristic. A quarter-wave sleeve may enclose the slotted assembly as shown in Fig. 12 to provide shielding and a ground terminal near the balanced leads.

O. M. Woodward Jr.

O. M. Woodward, Jr.

Appendix I

Balance Efficiency Calculation of Sleeve Balun

The sleeve balun is formed by a shorted sleeve, one-quarter wave in length at mid-band frequency, around the end of a coaxial line as shown in Fig. 13

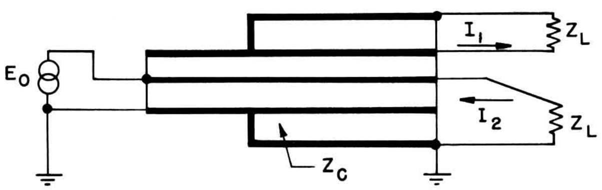


Fig. 13 – Schematic diagram of λ/4 sleeve balun feeding a balanced load.

where Z_c is the characteristic impedance of the line formed by the sleeve and the outer conductor of the coaxial line; θ is its length in electrical degrees; $2Z_L$ is the balanced load impedance.

The reactance presented by the end of the sleeve stub is:

$$Z_s = +jZ_c \tan\theta$$

The equivalent electrical circuit is given in Fig. 14, from which

$$I_o = I_2 = \frac{E_o}{Z_L + (Z_L Z_s / Z_L + Z_s)}$$

and

$$_1 = \frac{E_o\ (Z_s/Z_L + Z_s)}{Z_L + (Z_L Z_s/Z_L + Z_s)}$$

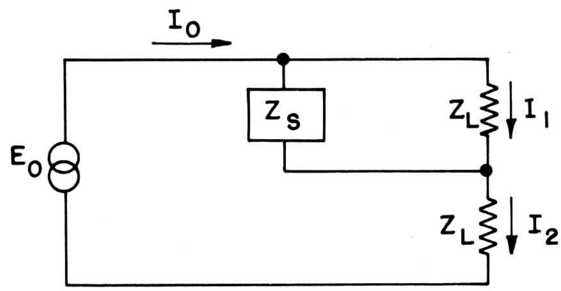


Fig. 14 – Equivalent electrical circuit.

Hence

$$R = \left|\frac{I_1 - I_2}{I_1 + I_2}\right| = \left|\frac{(Z_s/Z_L + Z_s) - 1}{(Z_s/Z_L + Z_s) + 1}\right| = \left|\frac{-1}{1 + (2Z_s/Z_L)}\right|$$

and the balance efficiency $= \frac{100}{1+R}$

From this it is seen that the balance bandwidth is broadened as the ratio Z_s/Z_L is increased. The greatest unbalance occurs when Z_s, and hence I_1, approaches zero. For I_1 to be zero, the components I_a and I_b must be equal and opposite in that leg of the load. Hence the ratio R is unity and the minimum balance efficiency becomes 50 per cent for this particular balun.

Appendix II

Balance Efficiency Calculation of Half-Wave Balun

This balun is formed from a phase-reversing cable one-half wave in length at mid-band frequency as shown in Fig. 15.

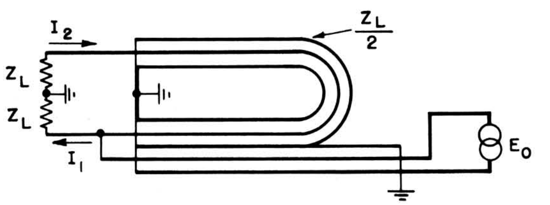


Fig. 15 - Schematic diagram of λ/2 balun feeding a balanced load.

With a balanced load, $2Z_L$, of 300 ohms, the 75-ohm characteristic impedance of the half-wave cable is equal to $Z_L/2$.

Rearranging the circuit as given in Fig. 16,

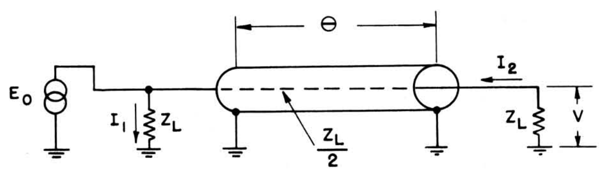


Fig. 16 - Equivalent electrical circuit.

from which

$$I_1 = E_0/Z_L$$

and using the usual transmission line equation;

$$-E_0 = I_2 Z_L \cos\theta + j\tfrac{1}{2} I_2 Z_L \sin\theta$$

where θ is the length of the phasing cable in electrical degrees.

Solving for

$$I_2 = \frac{-E_0}{Z_L(\cos\theta + j\frac{1}{2}\sin\theta)}$$

Then

$$R = \left|\frac{I_1 - I_2}{I_1 + I_2}\right| = \left|\frac{(\cos\theta + 1) + j\frac{1}{2}(\sin\theta)}{(\cos\theta - 1) + j\frac{1}{2}(\sin\theta)}\right|$$

from which the balance efficiency is calculated as before. A minimum balance efficiency of 0 per cent is obtained for phasing cables an integral number of wavelengths long.

The greatest impedance bandwidth is obtained from this type of balun when the phasing cable is matched, or equal to one-half of the balanced load impedance. However, it can be shown that the greatest balance bandwidth is obtained when the ratio of the load impedance to the phasing line impedance is made as large as possible.