ripple response, but the ripple varied between VSWR's of approximately 1.09 to 1.05. This difficulty was not surprising due to the extreme tapers required in the *a* and *b* dimensions, but a maximum VSWR of 1.05 was arrived at fairly easily by trial and error experimentation with the step dimensions.

It is interesting to note that further improvements probably could have been made on these transformer designs, since one of the RG-68/U castings tested did not exceed a maximum VSWR of 1.02 over the 7050 to 10,800-mc range. This outstanding performance can be attributed to the small dimensional variations which occur among many castings of the same design. Obviously, this particular casting possessed exactly the right combination of dimensions. However, for production purposes, a VSWR limit of 1.05 is much more practical since the tolerances which would have to be held to maintain the 1.02 limit are much too tight to be attainable.

Mechanical tolerances on these units presented some problems. In general, it was found that the distance between steps was relatively uncritical, but the height of the steps proved to be quite critical. Tolerances in the order of ±0.004 inch were found to be adequate for the section lengths, but changes as small as 0.0015 inch in the step heights introduced measurable differences in the VSWR patterns.

Despite the simplifying assumptions and small errors in the design method, the results obtained are very satisfactory, and it is felt that the design method has been proven to be reliable and accurate for this type of waveguide transformer.

A Wide-Band Balun*

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Summary—**Experimental results are given for a transformer from an unbalanced 50-ohm coaxial line to a balanced pair of 50-ohm coaxial lines. The design is one proposed by Marchand. The balance, standing wave ratio, and insertion loss are nearly constant over a 13 to 1 frequency range from 650 mc to 8500 mc. The standing wave ratio is less than 2.1 to one and the insertion loss is about 0.5 db over this band of frequencies.**

Introduction

SEVERAL authors[1–4] have presented theoretical analyses of devices suitable for transforming from a balanced to an unbalanced transmission line over a wide frequency range. It is the purpose of this paper to present some experimental results on a balun of the type described by Marchand[1] which provides satisfactory performance over a greater than ten to one band of frequencies extending from 650 to 8500 mc. One use for a balun with this sort of frequency coverage is in connection with microwave oscillators that can tune over frequency ranges of this order of magnitude and that can often be most effectively designed with balanced two-conductor interaction circuits.[5–7] The output of such tubes is in many cases most conveniently brought out of the vacuum envelope by means of two separate coaxial lines having a balanced signal between their center conductors. The balun to be described has been constructed to operate between such a two-coax system and a single coax, but only a slight change of the construction of the balanced output would be required to convert to a balanced shielded pair instead of two separate coaxial lines. Another possible use for a balun of this type would be as a microwave power splitter to obtain two equivalent outputs which differ in time phase by 180°.

Fig. 1 is a photograph of the balun. It transforms an unbalanced input signal supplied to the 50-ohm Hewlett-Packard G-76A receptacle input mounted on the brass cylinder into a balanced output signal appearing between the center conductors of the two 50-ohm RG5/U cables.

Fig. 2 is a schematic diagram of the device as proposed by Marchand.[8] Z_{OC} is the impedance of the unbalanced line C, Z_{OT} is the impedance of the large outer

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8 N. Marchand, *op. cit.*, Fig. 10.

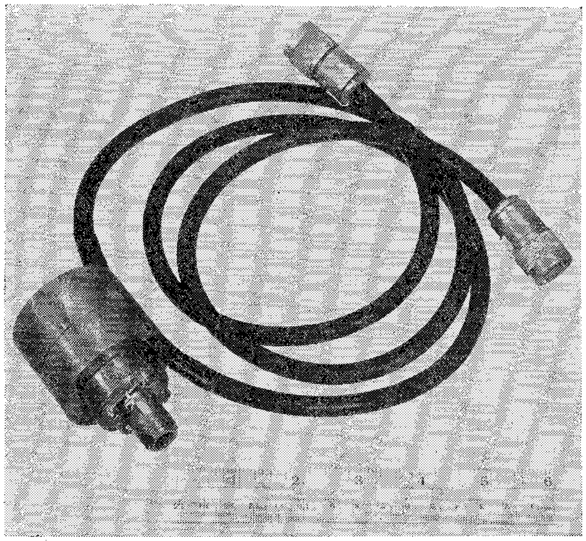

Fig. 1—An unbalanced input fed into the N-connector receptacle mounted in the brass cylinder is transformed into a balanced signal appearing between the two center conductors of the pieces of RG5/U cable coming out of the brass cylinder.

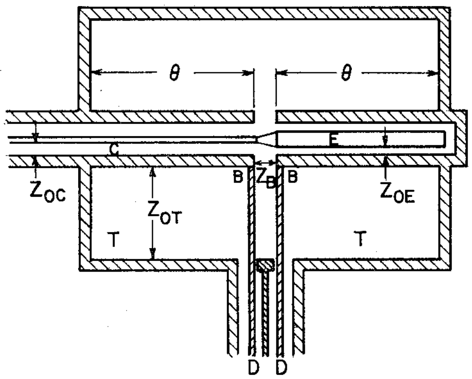

Fig. 2—A schematic drawing of the balun (after Marchand). The unbalanced line C drives the balanced line starting at BB. Two shorted coaxial stubs T, T use the outer conductors of coaxial lines C and E as their center conductors. The balanced line can be split into two separate coaxial lines D, D as shown, if desired.

shorted stubs T, Z_{OE} is the impedance of the small open-circuited stub E connecting directly to the unbalanced line, and Z_B is the impedance seen at the internal balanced line terminals, BB. Marchand shows that this impedance Z_B seen at the internal balanced terminals can be written in terms of Z_{OC}, Z_{OE}, and Z_{OT} as follows:

$$Z_B = Z_{OC} \frac{1 - j\dfrac{Z_{OE}}{Z_{OC}} \cot\theta}{1 - j\dfrac{Z_{OC}}{2Z_{OT}} \cot\theta - \dfrac{Z_{OE}}{2Z_{OT}} \cot^2\theta} \quad (1)$$

where θ is the electrical length of the shorted stub, as indicated in Fig. 2. The value of θ should be 90 degrees at mid-band and Z_{OE} should be chosen to make

$$Z_{OE} = \frac{(Z_{OC})^2}{2Z_{OT}}. \quad (2)$$

Z_{OT} should be made as large as possible.

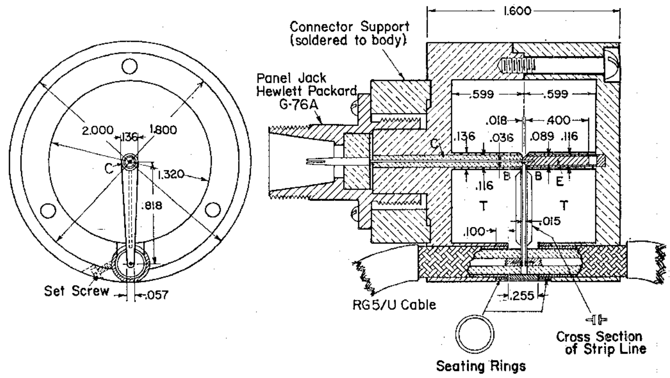

Fig. 3—A scale drawing of the balun shown in Fig. 1.

The design of the balun to be described used

$$Z_{OE} = 10.7 \text{ ohms}$$
$$Z_{OT} = 136 \text{ ohms}$$
$$Z_{OC} = 50 \text{ ohms}$$
$$Z_B = 50 \text{ ohms at 5 kmc.}$$

A tapered balanced strip line section was used to connect the internal balanced terminals to the two external coaxial lines, each of 50-ohms impedance. The tapered section transformed Z_B from 50 to 100 ohms at the connections to the external lines.

The physical arrangement used is shown in Fig. 3. Relevant dimensions are marked in inches and the labeling corresponds to Fig. 2. The internal section of unbalanced line C is RG141/U teflon cable with a solid outer conductor 0.010 thick. This outer conductor and the opposing extended stub were machined as integral parts of the main body. Since the two ends of the balanced strip line must be accurately spaced from each other by only 0.015, the two external coax lines must seat precisely in the body of the balun. This was accomplished by soldering the seating rings to the braid of these external lines before assembly. The cables are trimmed to extend the correct amount beyond the seating rings after the rings are soldered. The seating rings are held by set screws and the connections between the strip lines and the coax center conductors are made with flexible pins set into the center conductors.

Experimental Results

The VSWR looking into the unbalanced coax with the balanced coaxial lines terminated is an indication of how well the balun transforms from the 50-ohm unbalanced system to the 50-ohm internal balanced terminals, and also of how well the tapered strip line transforms from the 50-ohm internal balanced terminals to the 100-ohm external balanced terminals. Also included in the VSWR measurements are the effects of reflections from discontinuities in the transmission lines, and imperfections in the terminations. The measured plot of VSWR vs frequency shown in Fig. 4 includes all of these effects. The dotted curve in Fig. 4 shows the calculated

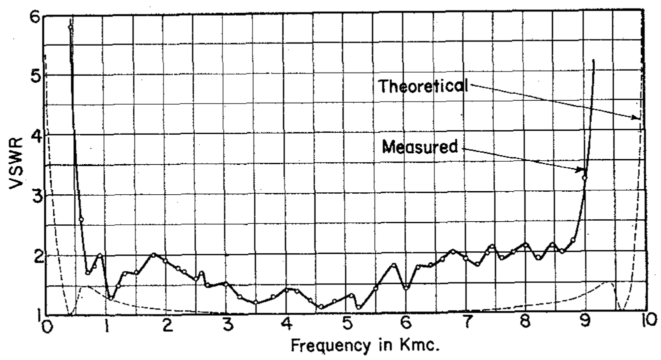

Fig. 4—A plot of standing wave ratio as a function of frequency looking into the unbalanced line *C* with terminations on both lines *D*, *D*. The dashed curve is a theoretical curve.

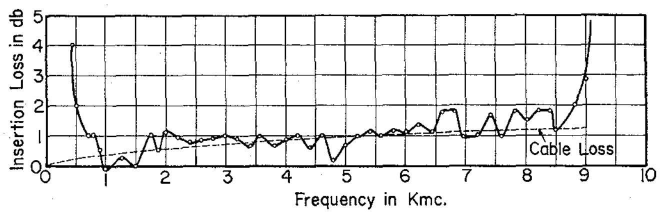

Fig. 5—A plot of insertion loss vs frequency through the balun for a signal fed into the unbalanced line *C*. The losses in the two RG-5/U cables varied as indicated by the dashed curve. The deviations of the insertion loss above and below the cable loss were caused by the mismatches between the various components used in the system. The actual loss of the balun is probably much less than 0.5 db.

values of VSWR which are theoretically ortainable from this design, neglecting any discontinuities or imperfections in the tapered strip line and terminations. The theoretical curve is obtained from

$$\text{VSWR} = \frac{Z_B}{Z_{OC}} \qquad Z_B > Z_{OC} \tag{3}$$

$$\text{VSWR} = \frac{Z_{OC}}{Z_B} \qquad Z_B < Z_{OC}. \tag{4}$$

Z_{OC} is the 50-ohm impedance of the unbalanced coaxial line. Z_B is the impedance at the internal balanced terminals as given by (1). The measured VSWR is below 2.1 from 0.65 to 8.5 kmc.

The insertion loss characteristics of this balun are plotted in Fig. 5. The measurements were made using the calibrated attenuator of a signal generator to compare the relative amounts of power transmitted to a crystal through a transmission system that first included the balun and then bypassed it. The difference between these two readings is the insertion loss in db. It is important to note that no special effort was made to match the impedances of the various components in either the presence or the absence of the balun. In the frequency range from 2 to 7 kmc a thermistor and power bridge were used to measure the actual power transmitted through the transmission system, first including, and then excluding the balun. The value of insertion loss over the frequency range from 0.65 to 6.5 kmc is less than 1.5 db. From 0.65 to 8.5 kmc the insertion loss is less than 2 db. An important source of loss in this setup was the loss of the two sections of RG5/U cable attached to the balun. Each was 2 feet long, so the cable loss varied from 0.4 db at 1 kmc to 1.2 db at 8 kmc and is indicated in Fig. 5 by the dashed line. The mismatches between the various components account for the deviations of the measured insertion loss above and below the cable loss. The actual total loss of the balun and the cable should be approximately the median value between the excursions of the measured insertion loss. Since it is apparent that the average of the measured curve only slightly exceeds the cable loss of the balun the results of the measurement seem quite reasonable. The deviations then are mainly the result of the mismatches at the various junctions and do not indicate precisely the net loss of the balun itself. It seems reasonable, however, that the actual loss at any frequency is much smaller than the deviations measured. In fact, the loss of the balun itself is probably much less than 0.5 db.

An experiment was performed to obtain some indication of the degree to which the two balanced outputs compared in amplitude and phase. This measurement was performed by applying a signal to the unbalanced input and connecting the two balanced outputs through 10-db coaxial attenuators to a slotted line. In this way the amplitude of the two signals could be compared by measuring the SWR and the phase could be compared by measuring the position of the central minimum. The attenuators differed only slightly so that a high degree of accuracy was possible in measuring the amplitudes. The positions of the attenuators were then reversed so that two different readings could be made and the effect of the attenuators could thereby be separated from the balun unbalance. In the range from 2 to 4 kmc the db difference between the two outputs of the balun was less than 0.38 db, and the average difference was 0.13 db. Over the same frequency range the deviation of the position of the central minimum was also observed. It was determined that the variation of phase shift through the other equipment was so great that it was impossible to obtain data which were truly representative of the small amount of phase shift present in the balun. It may be stated, however, that the phase shift was certainly much less than the peak-to-peak phase shift variation of 0.0012λ which was caused by the 10-db attenuators.