A Wide-Band Strip-Line Balun*

E. M. T. JONES† AND J. K. SHIMIZU†

Summary—**A new wide-band strip-line balun that uses a pair of dual coupled-strip-line band-pass filters is described. It can operate over bandwidths up to about 8:1 in the frequency range of about 100 to 10,000 mc. Design data and theoretical performance curves for typical wide-band baluns of this type are presented. The measured performance of an experimental balun operating over a 3:1 frequency range centered at 3000 mc is compared with the theoretical performance, and the effects of discontinuities and dissymmetries in the experimental balun are discussed.**

Introduction

A STRIP-LINE balun is used to connect an unbalanced structure, such as a single-conductor strip transmission line, to a balanced structure, such as a two-conductor strip transmission line or a balanced printed circuit antenna. Recently, several strip-line baluns[1] have been constructed that operate over a limited frequency band. The baluns described here can easily be designed to operate over several octaves.

One form of the wide-band strip-line balun is shown in Fig. 1(a). The balanced signal is obtained from the unbalanced signal by first dividing the signal into two parts, and then passing the divided signal through two equal-length coupled-strip-line band-pass filters.[2] These dual filters are one-quarter wavelength long at band center and have the property that the image phase shift of the upper filter (with the pair of shorted strips) is always 180 degrees greater than that of the lower filter (with the pair of open-circuited strips). At the frequencies where the normalized image impedances of the coupled-strip-line filters are equal to unity, the input VSWR of the balun is also unity and the ratio of balanced to unbalanced voltage at the output ports is infinite.

The other form of balun to be considered is shown in Fig. 1(b). It is similar to that of Fig. 1(a) except that one of the band-pass filters has been staggered with respect to the other one by a distance, l, equal to any odd multiple of a quarter wavelength at midband. This device has a ratio of balanced to unbalanced voltage of infinity at the output both when the distance l is equal to a quarter wavelength and when the image impedances of the two filters are equal. The input VSWR of this balun is unity, however, only when the image impedances of the filters are equal. Comparing the two forms of baluns of Fig. 1(a) and 1(b), the latter has the better balance-to-unbalance ratio, while the former has the better input match.

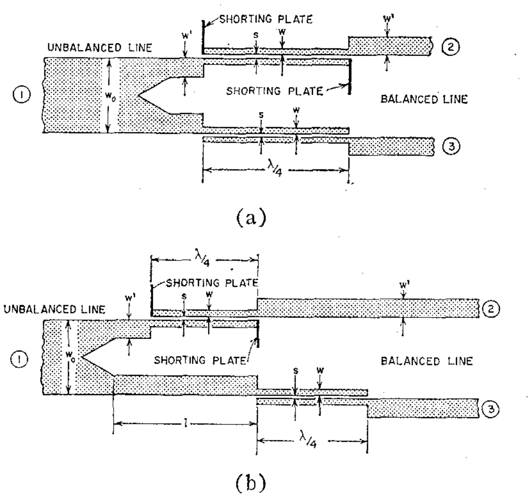

Fig. 1—Plan views of two wide-band strip-line baluns.

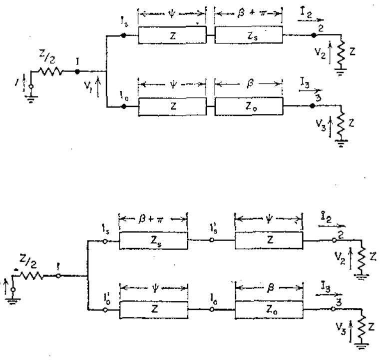

Fig. 2—Equivalent circuits of two wide-band baluns.

General Analysis

The equivalent circuit of the balun of Fig. 1(a) is shown in Fig. 2(a). The equivalent circuit of the balun in Fig. 1(b) with the staggered band-pass filters is shown in Fig. 2(b). The notation used is as follows.

$$Z_s = \frac{2Z_{oe}Z_{oo}\sin\theta}{[(Z_{oe}-Z_{oo})^2-(Z_{oe}+Z_{oo})^2\cos^2\theta]^{1/2}}$$

= image impedance of the band-pass filter with the pair of short-circuited strips.

$$Z_o = \frac{Z_{oe}Z_{oo}}{Z_s} = \text{image impedance of the band-pass}$$

filter with the pair of open-circuited strips.

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[1] E. G. Fubini, "Stripline radiators," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 149–156; March, 1955.

[2] E. M. T. Jones and J. T. Bolljahn, "Coupled-strip-transmission-line filters and directional couplers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 77–81; April, 1956.

Z_{oe} = characteristic impedance of one coupled strip, measured with respect to ground, with equal currents flowing in the same direction.

Z_{oo} = characteristic impedance of one coupled strip, measured with respect to ground, with equal currents flowing in opposite directions.

θ = electrical length of each band-pass filter.

$$\beta = \cos^{-1}\left[\left(\frac{Z_{oe}+Z_{oo}}{Z_{oe}-Z_{oo}}\right)\cos\theta\right]$$

= image phase shift of the filter with the pair of open-circuited strips.

$\beta + 180°$ = image phase shift of the filter with the pair of short-circuited strips.

ψ = electrical length of the transmission line of characteristic impedance, Z.

In each of these baluns the input impedances measured to the right at Ports 1_s and 1_o are duals, since the image impedances, Z_s and Z_o are chosen to satisfy

$$Z_s Z_o = Z^2. \tag{1}$$

The ratio of balanced to unbalanced voltage at Port 2 or Port 3 of either balun is

$$\frac{V_b}{V_u} = \left|\frac{1 - \dfrac{V_3}{V_2}}{1 + \dfrac{V_3}{V_2}}\right|. \tag{2}$$

$$\frac{V_3}{V_2} = -\frac{\cos\psi\left(\cos\beta + j\left(\dfrac{Z_s}{Z}\right)\sin\beta\right) + j\sin\psi\left(\cos\beta + j\left(\dfrac{Z_s}{Z}\right)\sin\beta\right)}{\cos\psi\left(\cos\beta + j\left(\dfrac{Z}{Z_s}\right)\sin\beta\right) + j\sin\psi\left(\cos\beta + j\left(\dfrac{Z_s}{Z}\right)\sin\beta\right)}. \tag{7}$$

For the balun of Fig. 1(a) the ratio V_3/V_2 may be expressed as

$$\frac{V_3}{V_2} = -\frac{\cos\beta + j\left(\dfrac{Z_s}{Z}\right)\sin\beta}{\cos\beta + j\left(\dfrac{Z}{Z_s}\right)\sin\beta}. \tag{3}$$

The normalized impedance Z_{1s}/Z measured to the right at Port 1_s and the normalized impedance Z_{1o}/Z measured to the right at Port 1_o are related to V_3/V_2 as

$$\frac{V_3}{V_2} = -\frac{Z_{1s}}{Z} = -\frac{Z}{Z_{1o}}. \tag{4}$$

The VSWR of the balun measured at Port 1 is

$$\text{VSWR} = \frac{1 + |r_{1s}|^2}{1 - |r_{1s}|^2} = \frac{1 + |r_{1o}|^2}{1 - |r_{1o}|^2} \tag{5}$$

where r_{1o}, the reflection coefficient at Port 1_o, is the negative of r_{1s}, the reflection coefficient at Port 1_s. Thus, the input VSWR of this balun with the unstaggered filters is a function only of the magnitude of the input reflection coefficient of either of its balanced branches. If the ratio of balanced to unbalanced voltage at the output ports is expressed in terms of the reflection coefficients, it is found that

$$\left|\frac{V_b}{V_u}\right| = \frac{1}{|r_{1s}|} = \frac{1}{|r_{1o}|}. \tag{6}$$

Eq. (6) shows that the ratio of balanced to unbalanced voltage of the balun with the unstaggered filters is also only a function of the magnitude of the reflection coefficient of either of its balanced branches. Note too that the balun performance is independent of the electrical length, ψ, of the transmission lines connecting to the two band-pass filters.

Returning now to the balun with the staggered filters shown in Fig. 1(b) it is found that the ratio V_3/V_2 may be expressed as

It is seen that $V_3/V_2 = -1$ corresponding to $V_b/V_u = \infty$ when $Z_s/Z = 1$ or when $\cos\psi = 0$.

The input impedance of the upper branch of the balun at Port 1_s is

$$\frac{Z_{1s}}{Z} = \frac{\cos\beta + j\dfrac{Z_s}{Z}\sin\beta}{\cos\beta + j\dfrac{Z}{Z_s}\sin\beta} \tag{8}$$

while that of the lower branch at Port $1_o'$ is

$$\frac{Z_{1o}'}{Z} = -\frac{\cos\psi\left(\cos\beta + j\left(\dfrac{Z}{Z_s}\right)\sin\beta\right) + j\sin\psi\left(\cos\beta + j\left(\dfrac{Z_s}{Z}\right)\sin\beta\right)}{\cos\psi\left(\cos\beta + j\left(\dfrac{Z_s}{Z}\right)\sin\beta\right) + j\sin\psi\left(\cos\beta + j\left(\dfrac{Z}{Z_s}\right)\sin\beta\right)}. \tag{9}$$

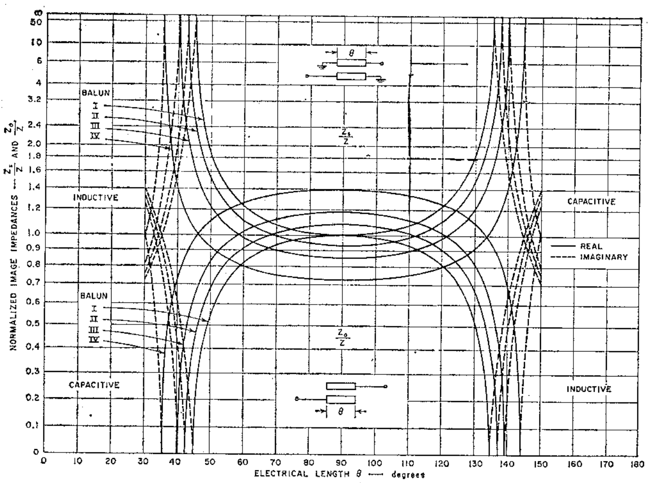

Fig. 3—Image impedance of the band-pass filters used in Baluns I, II, III, and IV.

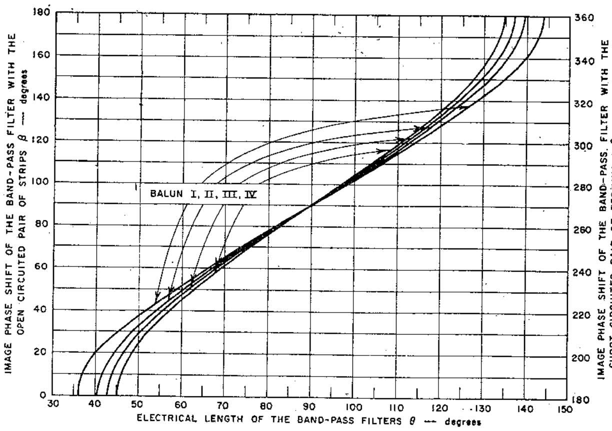

Fig. 4—Image phase shift of the band-pass filters used in Baluns I, II, III, and IV.

The input impedance at Port 1 normalized to the impedance $Z/2$ of the input line is

$$2Z_1/Z = \frac{2}{Z/Z_{1s} + Z/Z'_{1o}} \tag{10}$$

and the input VSWR in terms of the input impedance at Port 1 is

$$\text{VSWR} = \frac{|1 + 2Z_1/Z| + |1 - 2Z_1/Z|}{|1 + 2Z_1/Z| - |1 - 2Z_1/Z|}. \tag{11}$$

The VSWR is unity only when $Z_s/Z = 1$.

The Theoretical Performance of Wide-Band Baluns

Baluns with Two Unstaggered Band-Pass Filters of Equal Conductor Size

The frequency variation of the normalized image impedances, Z_s/Z and Z_o/Z, of the filters incorporated in these baluns is plotted in Fig. 3, and the frequency variation of the image phase shift of the filters is plotted in Fig. 4. The frequency variation of the input VSWR and the ratio of output balanced to unbalanced voltage, V_b/V_u, of four baluns with unstaggered band-pass filters is shown in Fig. 5. Table I summarizes their pertinent electrical parameters. It is seen that Balun I, which has $Z_s = Z_o = Z$ at midband, has unity VSWR and $V_b/V_u = \infty$ at midband.

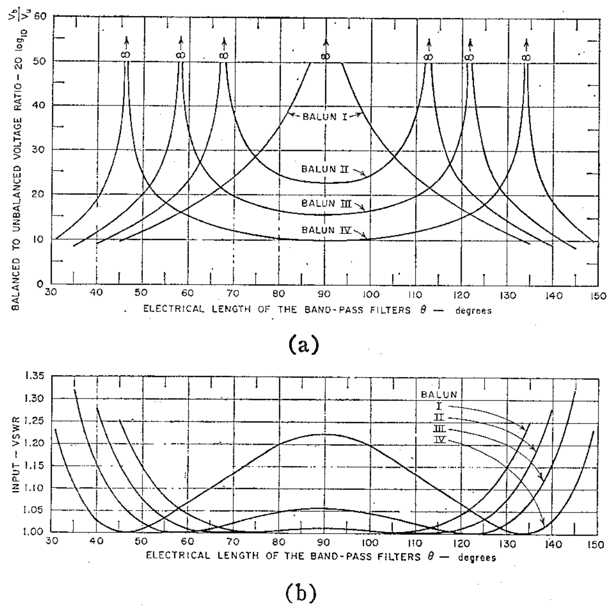

Fig. 5—Theoretical performance of Baluns I, II, III, and IV.

TABLE I

Summary of Electrical Parameters of Four Wide-Band Strip-Line Baluns, Each Having Two Unstaggered Band-Pass Filters of Equal Conductor Size

Parameter	Balun I	Balun II	Balun III	Balun IV
Z_{oe}/Z_{oo}	5.828	6.500	7.420	9.600
Z_{oe}/Z	2.415	2.250	2.730	3.200
Z_{oo}/Z	0.415	0.393	0.368	0.334
Z_s/Z (midband)	1.000	0.925	0.849	0.721
Z_o/Z (midband)	1.000	1.081	1.179	1.387
Design θ for perfect operation (degrees)	90±0	90±22.5	90±32	90±44

The frequency response of the VSWR has a maximally flat characteristic and is less than 1.018 over a 1.77:1 frequency range. The ratio of V_b/V_u over this frequency range is always greater than 20 db. Stated another way, the power in the unwanted unbalanced mode is always less than 1 per cent over this frequency range.

Baluns II, III, and IV are designed so that at midband $Z_o > Z$ and $Z_s < Z$, while maintaining the condition that $Z_sZ_o = Z^2$ at all frequencies. Inspection of the curves in Fig. 5 shows that increasing the ratio of Z_o/Z_s at midband increases the midband VSWR, decreases the midband ratio of V_b/V_u, and increases the separation of the frequencies of perfect balun operation. Balun IV, with a VSWR of 1.22 at midband, has a ratio of V_b/V_u of 3.16 at midband, corresponding to 10 per cent of the power in the unbalanced mode. Over a 4.76:1 frequency range, the performance of this balun is at least as good as at midband.

Between the output conductors of the balun there is a plane of symmetry characterized by the fact that electric field lines of the balanced mode are perpendicular to it while electric field lines of the unbalanced mode are parallel to it. In critical balun applications the unbalanced mode may be suppressed by inserting a resistance card along this plane. As an example, if the unbalanced mode is completely suppressed, Balun IV still has a power transfer efficiency of 90 per cent or better over a 4.76:1 frequency range.

Baluns with Two Band-Pass Filters of Different Conductor Size

General: When these baluns are constructed using two dual coupled-strip-line band-pass filters having different cross-sectional dimensions, it is found that for a given ratio of balanced to unbalanced impedance they possess much wider bandwidths than if the filters have conductors of the same dimensions. This behavior holds true whether or not the band-pass filters are staggered. In order for the filters with unequal conductor sizes to be duals (*i.e.*, $Z_sZ_o = Z^2$ at all frequencies) it is only necessary that ${}^sZ_{oe}/{}^sZ_{oo} = {}^oZ_{oe}/{}^oZ_{oo}$.[3]

Baluns with Two Unstaggered Band-Pass Filters of Different Conductor Size Having ${}^sZ_{oe}/{}^sZ_{oo} = 5.828$:[4] The frequency variation of the input VSWR and the ratio of the output balanced to unbalanced voltage V_b/V_u of four baluns, each having two unstaggered band-pass filters of different conductor size and ${}^sZ_{oe}/{}^sZ_{oo} = 5.828$, are shown in Fig. 6. Because the ${}^sZ_{oe}/{}^sZ_{oo}$ ratio for these baluns is the same as the Z_{oe}/Z_{oo} ratio of Balun I, the frequency variation of the normalized image impedances Z_s/Z and Z_o/Z is the same as that of Balun I. However, because the ${}^sZ_{oe}$ values for these baluns are smaller than Z_{oe} for Balun I, the Z_s/Z curves for these baluns are displaced downward from the Z_s/Z curve of Balun I, while the Z_o/Z curves are displaced upward. The frequency variation of the image phase shift for these filters is identical to that for Balun I and is shown in Fig. 4. Table II lists their pertinent electrical parameters.

Balun IIa is designed to have the same midband performance as Balun II; Balun IIIa to have the same midband performance as Balun III; and Balun IVa to have the same midband performance as Balun IV.

A comparison of the theoretical performance of Balun I of Fig. 5 to that of Baluns IIa and IIIa and IVa of Fig. 6 shows the improvement in balun bandwidth obtained by designing the two band-pass filters to have different conductor sizes while maintaining the ratio of even to odd characteristic impedance of the filters at 5.828. Here the bandwidth is defined as the frequency band over which the VSWR at the edges of the band equals that at the center. A comparison of the performance of Baluns II and IIa, III and IIIa, and IV and IVa shows that in each case the former balun has a slightly wider bandwidth. This increase in bandwidth, however, is achieved at the expense of using filters with higher ratios of even to odd characteristic impedance that are much harder to construct. Hence, it is believed that in most applications it is preferable to construct baluns containing filters with unequal conductor dimensions.

Baluns With Two Unstaggered Band-Pass Filters Having ${}^sZ_{oe}/{}^sZ_{oo} = 17.399$:[5] The bandwidth of extremely-wide-band baluns is approximately proportional to the logarithm of the ratio of ground-plane spacing to conductor cross-section dimensions in the band-pass filters. Hence the maximum practical bandwidth of extremely wide-band baluns which have very small center conductor dimensions is determined by mechanical con-

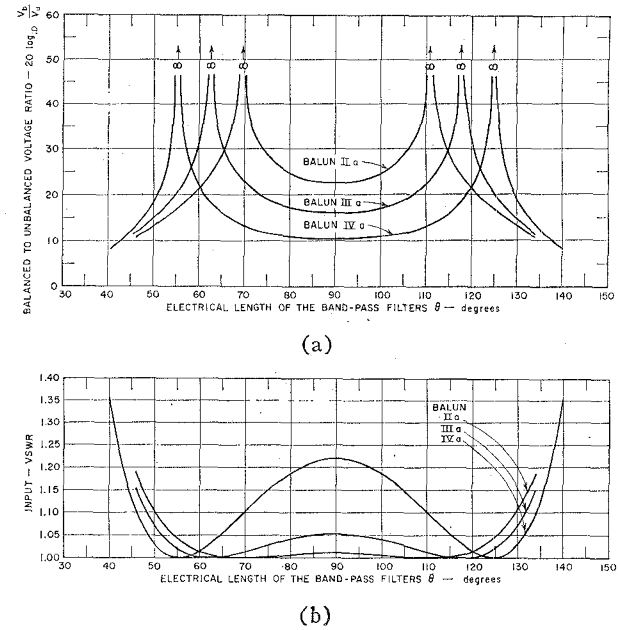

Fig. 6—Theoretical performance of Baluns IIa, IIIa, and IVa.

TABLE II

SUMMARY OF ELECTRICAL PARAMETERS OF THREE WIDE-BAND STRIP-LINE BALUNS EACH HAVING TWO UNSTAGGERED BAND-PASS FILTERS OF UNEQUAL CONDUCTOR SIZE

Parameter	Balun		
	IIa	IIIa	IVa
${}^sZ_{oe}/{}^sZ_{oo} = {}^oZ_{oe}/{}^oZ_{oo}$	5.828	5.828	5.828
${}^sZ_{oe}/Z$	2.233	2.049	1.740
${}^sZ_{oo}/Z$	0.383	0.351	0.298
${}^oZ_{oe}/Z$	2.609	2.846	3.348
${}^oZ_{oo}/Z$	0.447	0.488	0.574
Z_s/Z (midband)	0.925	0.849	0.721
Z_o/Z (midband)	1.081	1.179	1.387
Design θ for perfect operation (degrees)	90±21	90±28	90±35

[3] Superscripts *s* and *o* denote band-pass filters with short and open-circuited parts, respectively.

[4] A directional coupler of the type described by Jones and Bolljahn, *op. cit.*, with $Z_{oe}/Z_{oo} = 5.828$ would have a midband coupling of −3 db.

[5] A directional coupler of the type described by Jones and Bolljahn, *op. cit.*, with $Z_{oe}/Z_{oo} = 17.399$ would have a midband coupling of −1 db.

TABLE III

SUMMARY OF ELECTRICAL PARAMETERS OF FOUR WIDE-BAND STRIP-LINE BALUNS EACH HAVING TWO UNSTAGGERED BAND-PASS FILTERS OF UNEQUAL CONDUCTOR SIZE

Parameter	Balun			
	V	VI	VII	VIII
$\frac{{}^sZ_{oe}}{{}^oZ_{oo}} = \frac{{}^oZ_{oe}}{{}^oZ_{oo}}$	17.399	17.399	17.399	17.399
${}^sZ_{oe}/Z$	8.117	7.944	7.413	5.911
${}^sZ_{oo}/Z$	0.466	0.456	0.426	0.339
${}^oZ_{oe}/Z$	2.143	2.189	2.346	2.943
${}^oZ_{oo}/Z$	0.123	0.125	0.135	0.169
Z_s/Z (midband)	0.990	0.968	0.904	0.721
Z_o/Z (midband)	1.010	1.032	1.106	1.387
Design θ for perfect operation (degrees)	90± 15.47	90± 25.96	90± 39.97	90± 53.73

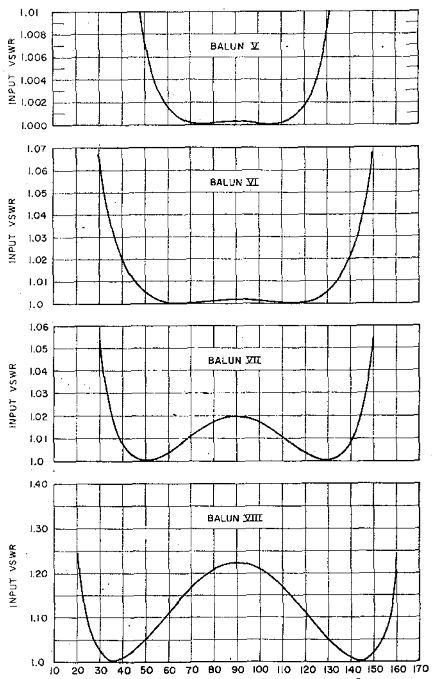

Fig. 7—Theoretical input VSWR of Baluns V, VI, VII, and VIII.

struction tolerances. Baluns V, VI, VII, and VIII have been selected for consideration here because their band-pass filters have conductors whose cross-section dimensions are about as small as can be constructed conveniently.

Table III summarizes the pertinent electrical parameters of these baluns. The frequency variation of the input VSWR of these baluns is shown in Fig. 7, and the ratio of the output balanced to unbalanced voltage, V_b/V_u, is shown in Fig. 8. Inspection of the curves in Figs. 7 and 8 shows that increasing the ratio of Z_o/Z_s at midband increases the midband VSWR, decreases the midband ratio of V_b/V_u, and increases the separation of the frequencies of perfect balun operation.

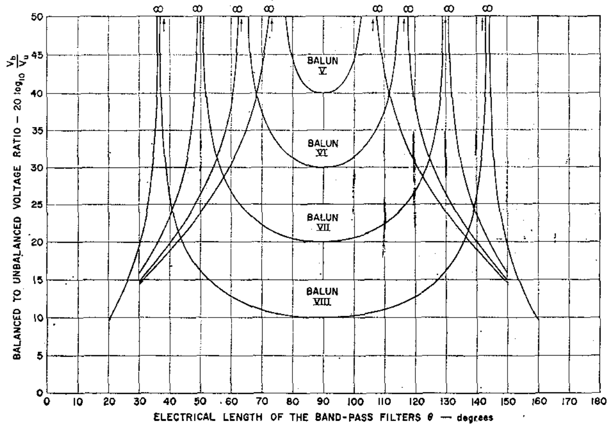

Fig. 8—Theoretical balanced to unbalanced voltage ratio, V_b/V_u, of Baluns V, VI, VII, and VIII.

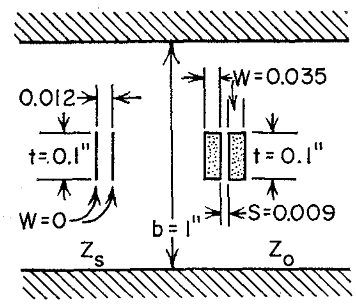

Fig. 9—Cross section of a coupled strip-line region of Balun VIII.

Fig. 7 shows that Baluns V, VI, VII, and VIII have maximum VSWR of 1.0002, 1.002, 1.020, and 1.220, respectively, over the corresponding bandwidth of 1.65, 2.34, 4.00, and 7.74:1. In Fig. 8, the curves of V_b/V_u indicate that for these baluns the corresponding minimum percentage power transfer efficiency over the operating frequency band is 99.99, 99.90, 99.00, and 90.00. Comparison between Baluns IV and VIII, where both baluns have a VSWR of 1.22 and a ratio V_b/V_u of 3.16 at midband, shows that the performance of Balun VIII is at least as good as at midband over 1.626 times the frequency range that can be obtained with Balun IV.

Fig. 9 illustrates the approximate cross-section dimensions of the coupled strips of the two band-pass filters of Balun VIII when the impedance Z is 100 ohms, and the cross section is air filled. If the cross section were filled with dielectric to support the conductors their dimensions would be even smaller. Nevertheless, it is believed that with care this balun could be constructed with either an air-filled or dielectric-filled cross section with sufficient precision that its measured performance would be close to the theoretical performance.

Balun With Two Staggered Band-Pass Filters of Different Conductor Size:[6] This section describes the frequency variation of the input VSWR and output bal-

[6] The staggering technique can also be applied to baluns that have filters with equal cross-section dimensions.

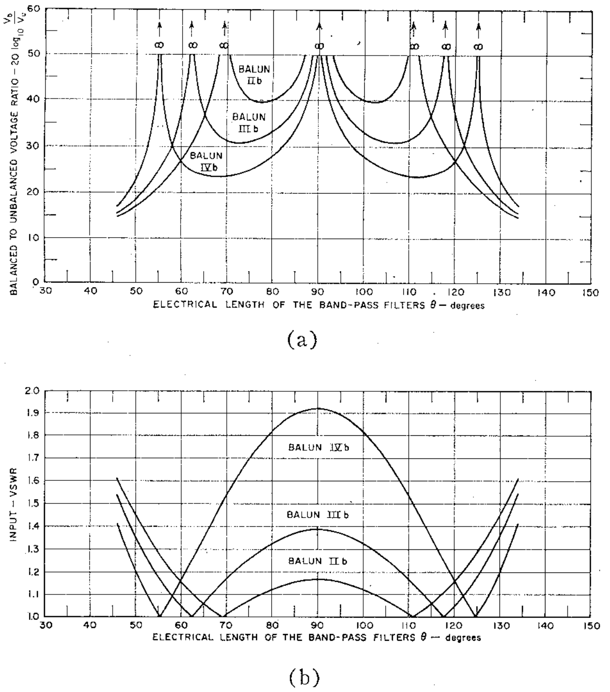

Fig. 10—Theoretical performance of Baluns IIb, IIIb, and IVb.

anced to unbalanced voltage ratio of three baluns having staggered band-pass filters. Each of these baluns utilizes two staggered coupled-strip-line band-pass filters having dual input impedances but different cross-sectional dimensions. The electrical parameters of Baluns IIb, IIIb, and IVb are the same as those of Baluns IIa, IIIa, and IVa with the single important difference that one of the band-pass filters in each of Baluns IIb, IIIb, and IVb is staggered with respect to the other by a distance l equal to one-quarter wavelength at midband.

The ratio of balanced to unbalanced output voltage of these baluns is plotted in Fig. 10(a), while the input VSWR is shown in Fig. 10(b). It is seen by comparing Fig. 10(a) to Fig. 6(b) that this quarter-wavelength staggering greatly increases the ratio of balanced to unbalanced voltage over the band, while a comparison between Fig. 10(b) and Fig. 6(b) shows that the staggering also increases the average input VSWR.

Experimental Model of Balun I

Construction

An experimental model of Balun I was constructed which had the electrical parameters given in Table I, and a center frequency of 3 kmc. Its dimensions are listed in Table IV. A photograph of this balun is shown in Fig. 11. For convenience in measuring the performance of this balun with standard measuring equipment (normally at a 50-ohm level), the output terminal impedance was transformed from 100 ohms to 50 ohms in five steps. This transformer was designed to have an "equal-ripple" VSWR response, with a maximum

TABLE IV

Dimensions of Experimental Model of Balun I

	Dimension (fractions of an inch)
Ground-plane spacing b	0.500
Thickness t of all strips	0.062
Width w' of strip having Z of 100 ohms	0.147
Width w_o of strip having $Z/2$ of 50 ohms	0.555
Width w of strips in band-pass filters	0.033
Spacing s between strips in band-pass filters	0.0166
Length l of band-pass filters	0.984

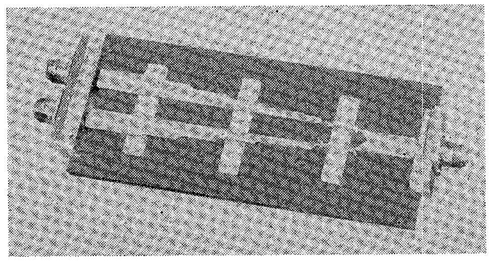

Fig. 11—Photograph showing the internal construction of experimental strip-line Balun I.

VSWR of 1.065 over the frequency band of 3.5:1.[7] The length of each transformer is 0.984 inch, while the width of the strips in the stepped transformer is 0.485, 0.372, 0.262, and 0.187 inch. In order to reduce discontinuity effects in the balun at places where there are sudden changes in strip cross section, tapers were provided at each transformer step and a V-shaped notch was placed at the power divider. In Fig. 11, the strips are shown supported with polyfoam blocks and with small polystyrene spacers inserted between the strips at four places to maintain the coupling spacing uniform.

Experimental Results

The balanced to unbalanced voltage ratio, V_b/V_u, of the balun was computed by means of (2), using the measured values of the magnitude and phase of V_3/V_2 at the output terminals.

The measured VSWR and V_b/V_u ratio compared with the theoretical values are plotted in Fig. 12. It is seen that the measured values deviate from the theoretical values; nevertheless, the experimental balun has good performance since the V_b/V_u ratio is greater than 11.4 db over a 3:1 frequency range. It is believed that the deviation between the theoretical and experimental values of V_b/V_u is caused by discontinuities and physical dissymmetries of the arms of the balun containing the band-pass filters. The relatively high VSWR of the input line is undoubtedly caused by a symmetrically located discontinuity at the power divider. Some idea of the magnitude of this latter discontinuity can be in-

[7] S. B. Cohn, "Optimum design of stepped transmission-line transformers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 16–21; April, 1955.

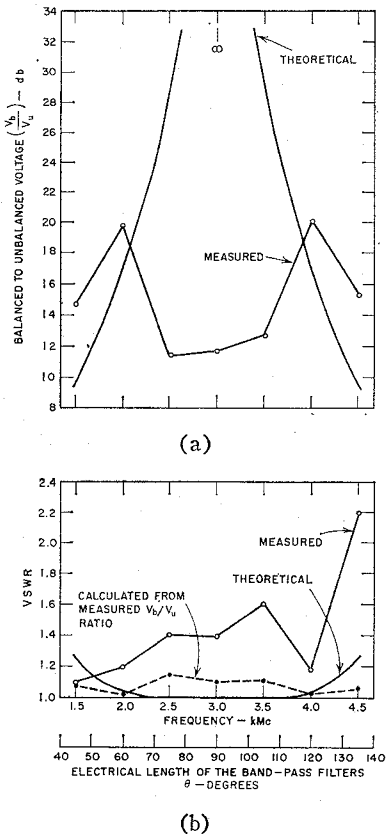

Fig. 12—Experimental performance of strip-line Balun I.

ferred by comparing the measured VSWR in Fig. 12 with the VSWR calculated from the measured V_b/V_u ratio by means of (5) and (6).

Conclusions

The theoretical analysis of these baluns has shown that they have good wide-band performance. The baluns using unstaggered band-pass filters have a very low VSWR over their operating frequency range; in comparison, the baluns using staggered band-pass filters have a higher input VSWR, but a better balance of the output voltage over the same bandwidth. However, in either type of balun the balanced to unbalanced voltage ratio may be greatly increased by inserting a suitably oriented resistance card between the strips connecting to the output ports.

The measured performance of the experimental balun is good over a 3:1 frequency range, although the experimental performance agrees only approximately with theory, because of discontinuity effects. It is believed that, by reducing junction discontinuities, the balun performance can be made to conform closely to the theoretical results.

Acknowledgment

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Periodic Structures in Trough Waveguide*

A. A. OLINER† AND W. ROTMAN‡

Summary—**The center fin in trough waveguide can be modified in a periodic fashion to alter the propagation characteristics of the guide. Two such periodic modifications, one an array of circular holes and the second a periodic array of teeth, have been measured fairly extensively and analyzed theoretically. These configurations are useful in connection with antenna scanning or waveguide filter applications.**

The array of holes produces only a mild slowing of the propagating wave, but the toothed structure, which may alternatively be described as a series of flat strips extending beyond the edge of the fin, can cause the propagating wave to vary from a very slow to a very fast wave. The periodic structures are theoretically treated by two methods, a transverse resonance procedure and a periodic cell approach. These theoretical results agree very well with each other and with the measured data.

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I. Introduction

Trough waveguide is a relatively new waveguide type possessing a number of interesting properties. The geometry of the guide is shown in Fig. 1. It is derived from symmetrical strip transmission line by placing a short circuit at the midplane of the latter;[1] for this reason, the dominant mode in trough waveguide is identical with the first higher mode in the strip transmission line. The electric field distribution is indicated in Fig. 1 as being oppositely directed in the top and bottom portions; hence, if the plate spacing in the region beyond the edge of the center fin is less than a half wavelength, the field is of the below cutoff type in this outer region when viewed in the transverse direction. Thus, by virtue of symmetry, one of the guide walls is reactive and the structure is non-radiating.

[1] Airborne Instruments Lab., advertisement on trough waveguide, Proc. IRE, vol. 44, p. 2A; August, 1956.