Oct. 18, 1949. R. S. WEHNER 2,485,177

BROAD-BAND ANTENNA SYSTEM

Filed Feb. 28, 1946 3 Sheets-Sheet 1

Fig. 1.

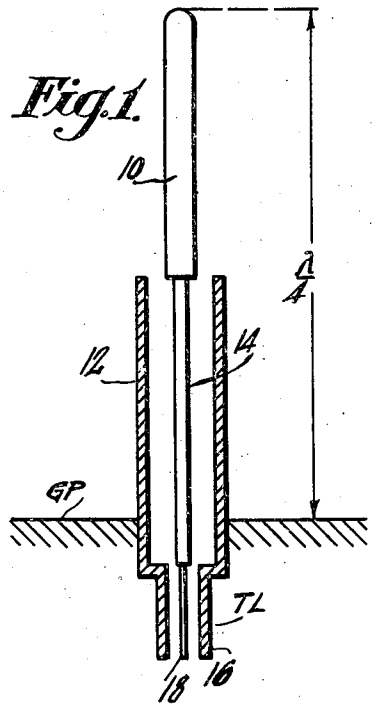


Fig. 2.

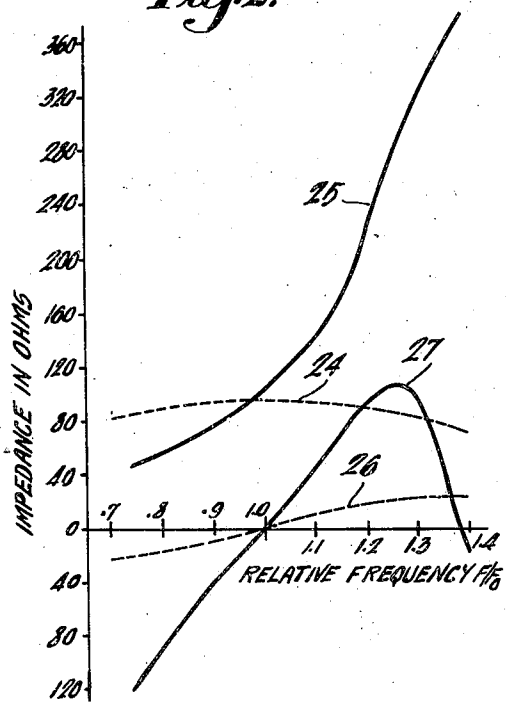


Fig. 3.

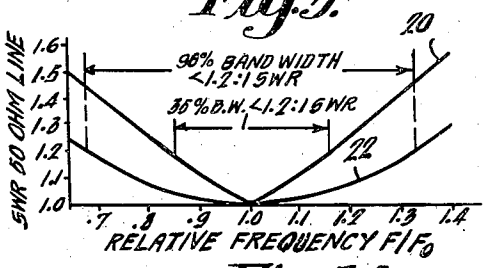
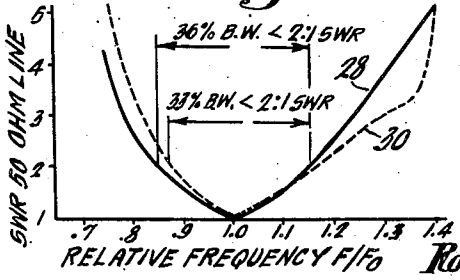


Fig. 3A.



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BROAD-BAND ANTENNA SYSTEM

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Fig. 4.

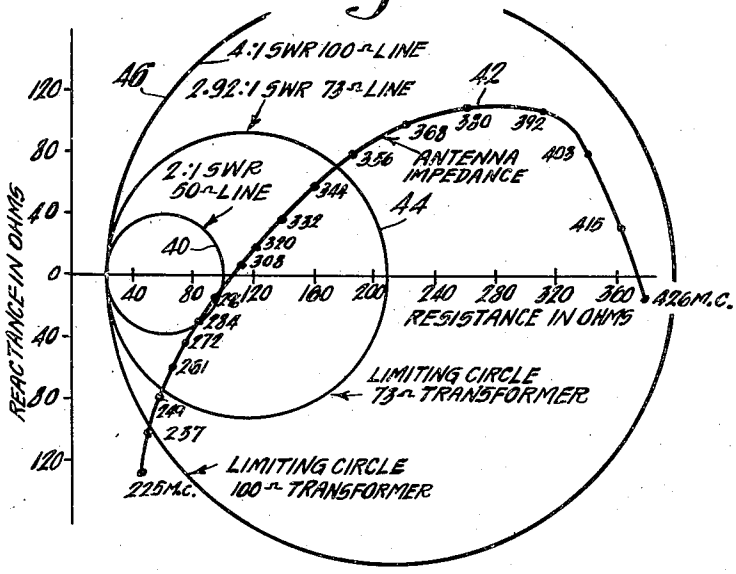
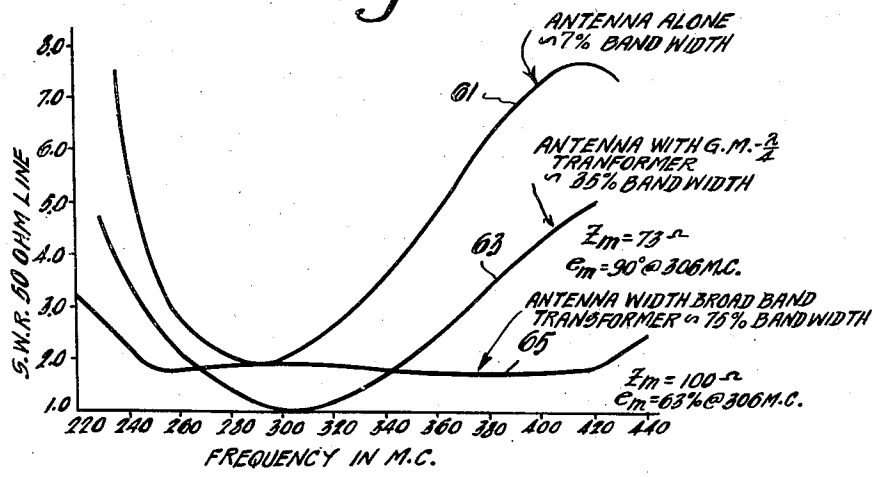


Fig. 6.



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BROAD-BAND ANTENNA SYSTEM

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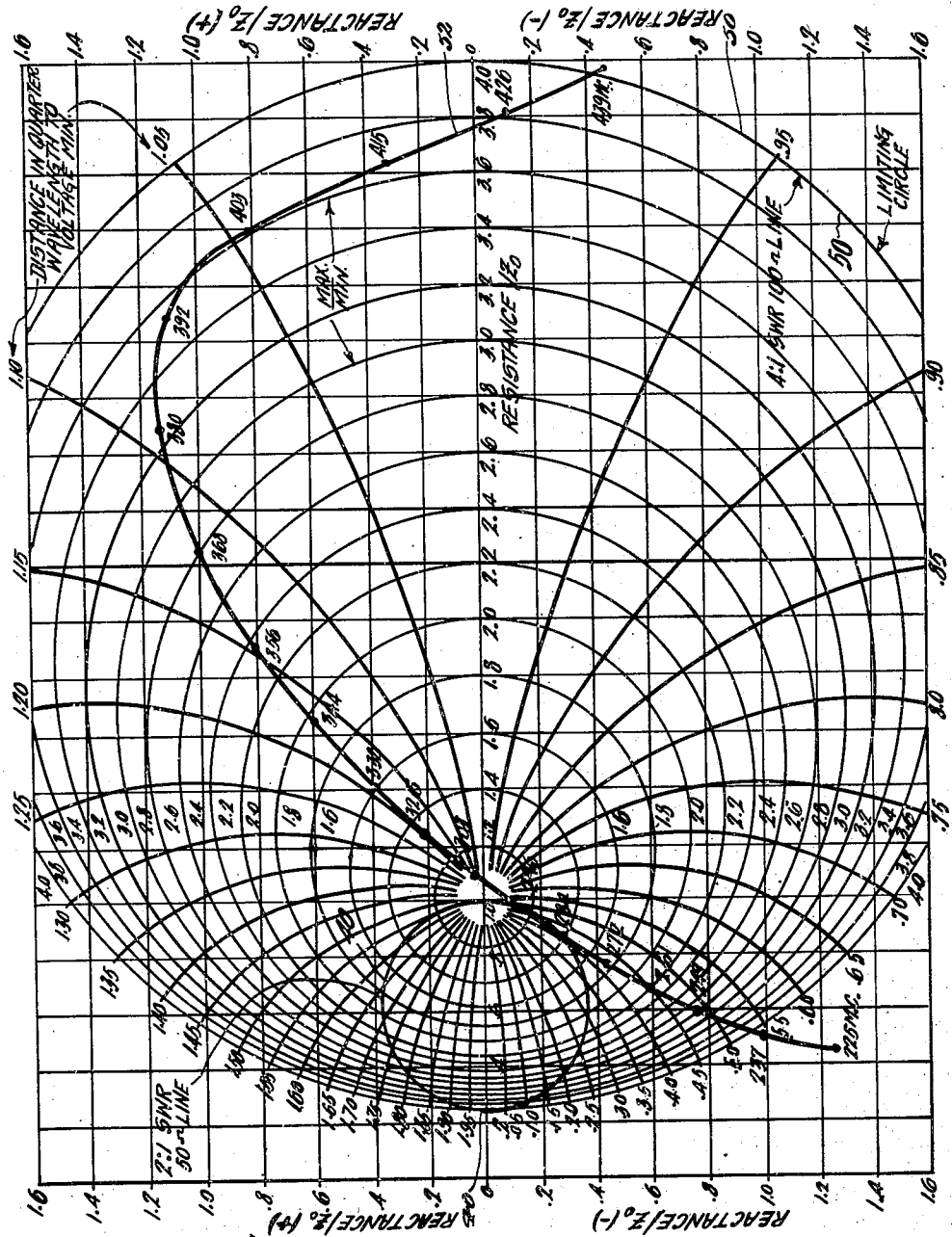


Fig. 5.

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BROAD-BAND ANTENNA SYSTEM

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19 Claims. (Cl. 250—33)

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The present invention relates to broad-band antenna systems and more particularly to an arrangement of a series transformer matching section for obtaining the broad-band characteristics in a comparatively small simple antenna.

An object of the present invention is the provision of an antenna and transformer matching section which has extremely broad-band characteristics.

Another object of the present invention is the provision of an antenna system which is mechanically and aerodynamically practical in high-speed aircraft.

Another object of the present invention is the provision of a broad-band antenna which attains its broad-band characteristics along purely electrical lines.

Another object of the present invention is the provision of a matching system between an antenna and transmission line such that over a broad band of frequencies the original reflection due to mismatching at the antenna terminals is cancelled by additional sources of reflection.

A further object of the present invention is the provision of an antenna and impedance matching section which is entirely self contained.

A further object of the present invention is the provision of an antenna matching transformer which may be installed in confined places which are too small to allow the use of conventional impedance matching systems.

The present invention is particularly designed to be used with an antenna having a high input impedance. The particular means of obtaining a high input impedance for the antenna is not, of itself, a part of the present invention. However, for the purposes of disclosing the invention, the particular type of high input impedance antenna, the sleeve type, is illustrated and the description related thereto. However, it should be clearly understood that it is within the scope of the present invention to use other types of antenna construction. All that is necessary as far as the antenna is concerned is that its impedance be substantially greater than that of the transmission line with which it is to be operated. A series impedance matching section is connected between the feed point of the antenna and the associated transmission line coupling the antenna to the transmitter, said matching section having a characteristic impedance which is substantially higher than heretofore commonly used geometric means between the antenna and transmission line impedance.

The present invention will be more fully understood by reference to the following detailed description in which:

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Figure 1 illustrates, in plan view and partly in section, one type of antenna to which the matching section of the present invention has been applied;

Figure 2 is a family of curves illustrating the variation in impedance of an actual antenna with a change in frequency as compared with a hypothetical ideal antenna;

Figure 3 is a family of curves illustrating the effect on band width of various matching sections when used to match a constant impedance simulated antenna of ideal characteristics. Figure 3A is a similar family of curves showing the effects of the same matching sections when used to match the typical actual antenna, whose characteristics have been plotted in Figure 2;

Figure 4 is a chart illustrating in different form the variation in impedance of the antenna of Figure 2 with changes in frequency, while

Figure 5 is a chart illustrating in somewhat different form the variation in antenna impedance with a variation in frequency, while

Figure 6 is a family of curves illustrating the comparative band width which may be obtained with a high impedance antenna, for example, such as shown in Figure 1, with different types of matching transformers.

In many radio applications it is important that the input impedance of the antenna be matched or nearly matched to the characteristic impedance of the feeding transmission line over a wide range of frequencies. The most direct means heretofore known for securing broad-band input characteristics consists in using an antenna having a cross-section of the same order of magnitude as its length, the large-area radiating surface of this structure being fed from the small-sized transmission line through transitional tapered line sections in a manner resulting in impedance characteristics which are slowly varying functions of frequency to either side of resonance. If the structure is so proportioned that its resonant impedance (or impedance level) matches or comes close to matching the line, then the antenna will automatically be matched over a more or less wide range of frequencies, simply because its impedance does not change appreciably as the frequency departs from resonance. The band width attainable with such a radiator is limited only by its transverse size relative to its length, or by its size relative to the operating wavelength, the impedance match being better and the range of frequencies over

which the match exists being greater the larger the antenna, assuming, of course, that it is adjusted to have the proper impedance level to begin with and that it is fed in a manner which takes full advantage of its large radiating surfaces. That is, in a manner which makes the transition as gradual as possible from the field mode which exists and is propagated along the feed line to that which can exist and be propagated in space.

While such intrinsically broad-band antennas have the advantage of electrical simplicity, their application is limited to fixed installations or to very high frequencies such that dimensions large in terms of wavelengths are physically small. But in many mobile installations, particularly in aircraft radio at frequencies below 1000 megacycles, their use is precluded by their large size, which may involve mechanical, aerodynamic, and tactical difficulties which are quite unsurmountable. In such cases it is necessary to use an antenna structure which is mechanically and aerodynamically practical, and such an antenna, necessarily of small cross-section, is likely to have input impedance characteristics which are relatively rapidly varying functions of frequency and which are by no means intrinsically broad band. The approach to broad banding the antenna must then be along purely electrical lines, consisting in the use of matching sections i. e. circuits of lumped or distributed elements inserted between the antenna terminals and the feed line, the purpose of which is to introduce into the transmission line system an additional source or sources of reflection the magnitude and phase of which are such as to cancel, wholly or partially, and over a more or less wide range of frequencies, the original reflection due to the mismatch at the antenna terminals.

The most simple impedance matching section suitable for use at frequencies of the order of and higher than 30 megacycles is a simple series transformer line section which may be associated with an antenna. For the purpose of illustration only, an antenna such as shown in Figure 1 may be used. The radiator proper for this example is denoted by reference numeral 10 and includes a short rod protruding from a sleeve portion 12 forming the lower half of the antenna. Within sleeve 12 is an impedance matching section for matching the antenna to transmission line TL. The inside diameter of sleeve 12 and the diameter of inner rod 14 are so related as to obtain the desired characteristic impedance of the series section for matching purposes. At the lower end of the impedance matching section and below ground plane GP the outer shell 16 of transmission line TL is connected to the shell 12 and ground plane GP while inner conductor 18 is connected to the lower end of rod 14.

In heretofore known forms of construction the impedance matching section 12, 14 was so dimensioned as to obtain a characteristic impedance which was the geometric mean between the impedance of the antenna formed by radiator 10 and the outer surface of sleeve 12 and the characteristic impedance of transmission line TL. Generally, the overall length of the matching section was so chosen as to be a quarter wave at the midband of the operating band of frequencies. This followed from the relationship that any pure resistance R_0 could be matched at a single frequency to a line of any characteristic impedance Z_0, by means of a series impedance matching transformer having an impedance Z_m, equal to the square root of the product of R_0 and Z_0. Since a great many antennas are operated at, or in the immediate vicinity of, resonance, where their input impedance is purely resistive, for spot frequency or very narrow-band operation such quarter geometric mean transformers were satisfactory.

Even for an appreciable range of frequencies to either side of the matching frequency a fairly good match is obtained. The band width thus obtained depends upon the transformation ratio and upon the standard of matching required, being less the greater the departure of the ratio

$$\frac{R_0}{Z}$$

from unity and less the smaller the maximum tolerable standing wave ratio on the main transmission line connected to the antenna. If the transformation ratio is not too great and if the degree of match required is not too perfect, considerable band widths may be obtained with a quarter wave geometric mean transformer between a constant pure resistance and a transmission line. Thus, for example, a constant resistance of 106 ohms may be matched to a 50 ohm line by means of a 73 ohm transformer, 73 being the geometric mean between 50 and 106. As shown in Figure 3 by curve 20, the transformer yields less than 1.2:1 standing wave ratio over a frequency band approximately 35% in width.

The percentage band width here referred to is defined as:

$$BW=\left(\frac{F_{max}}{F_{min}}-1\right)\times 100\%$$

where F_{max} and F_{min} are the upper and lower frequency limits to the band over which the matched standing wave ratio is less than the specified maximum.

The effectiveness of the quarter wave geometric mean transformer in matching a pure and constant resistance to a line may be greatly increased by carrying out the transformation in two or more steps; that is, by using two or more quarter wave geometric mean transformers in cascade. That is, in the preceding case of matching a 106 ohm load to a 50 ohm line, the transformer nearest the antenna should have a characteristic impedance of 87.5 ohms, 87.5 being the geometric mean of 106 and 73, 73 being the geometric mean of 106 and 50. The transformer should be a quarter wave in length at midband. The second transformer of equal length should have a characteristic impedance of 60 ohms, 60 being the geometric mean of 73 and 50.

As shown in curve 22 in Figure 3 the double transformer gives a much better match in the vicinity of midband, the standing wave ratio being nearly one for an appreciable range of frequencies. About 96% band width is obtained with a 1.2:1 standing wave ratio on a 50 ohm line. This is almost a three-fold increase over the band width yielded by a single transformer. This principle of transformers in cascade may be extended to any desired extent, the greater the number of transformers in series the greater the band and better the match. This is, however, only true as far as matching a constant pure resistance is concerned.

However, when it comes to matching an antenna having a complex input impedance with resistance and reactance both more or less rapidly varying functions of frequency, the band width and degree of perfection of match yielded by

quarter wave geometric mean transformers is definitely limited. The principal reason for limitation is evident upon inspection of Figure 2. Dashed lines 24 and 26 of Figure 2 represent the variation in resistance and reactance of an ideal termination of a quarter wave geometric mean transformer for a 2:1 transformation from an impedance level of 100 ohms down to a 50 ohm line. By "ideal" I mean that a quarter wave geometric mean transformer, terminated in an impedance the resistive and reactive components of which vary with frequency in the manner shown by dashed curves 24 and 26, will have an input impedance of exactly 50 ohms (matching the line perfectly) over the entire range of frequencies. These particular numbers were selected to facilitate comparison with an actual problem to be discussed later though any reasonable values would show the same result. It will be noted that the resistance-frequency characteristic shown by dashed line 24 is a flat bell-shaped curve with its peak at midband frequency and decreasing to either side of resonance. The ideal reactance frequency curve (dashed line 26) is typical of a series resonance circuit or antenna but is a very slowly varying function of frequency. If an actual series resonant antenna could be made to have these characteristics, it could be matched perfectly over a very wide range of frequencies. However, the characteristics of actual antennas do not even closely approximate this ideal. For example, curves 25 and 27 of Figure 2 illustrate the true input impedances of an actual antenna, having an impedance level of the order of 100 ohms, and about as large in cross-section as mechanically and aerodynamically practical for use in aircraft in the frequency region of around 300 megacycles per second. It will be seen that the resistance curve 25 is very steep, the resistance above resonance increasing rather than decreasing. Furthermore, the resistance increases at a much greater rate than it should be desirable for it to decrease. The reactance curve 27 likewise is excessively steep for perfect broad-band matching. In spite of any attempts made to force the antenna to approach the ideal characteristic more closely, as far as their slopes are concerned, by increasing the cross-section of the antenna, the input resistance will always increase with increasing frequency in the vicinity of resonance. This fact limits the usefulness of quarter wave geometric mean transformers as applied to physical realizable antennas.

However, an example will be given as to the effect of a quarter wave transformer in broad banding a simple antenna having the characteristics given by curves 25 and 27 of Figure 3. As shown by curve 28 in Figure 3A, an antenna having a resonant resistance of 106 ohms can be perfectly matched at resonance to a 50 ohm line by means of quarter wave geometric mean transformer, yielding 36% band width with less than a 2:1 standing wave ratio on a 50 ohm line. This band width is much smaller and the degree of matching much worse than that yielded by the same transformer terminated in a 106 ohm pure resistance (curve 20 of Figure 3) but it nevertheless is an appreciable improvement over the unmatched antenna. If a considerably wider band width is required, the use of two quarter wave geometric mean transformers in cascade does not, as might be expected, result in any improvement. The dotted curve 30 of Figure 3, it will be noted, shows that two transformers in cascade yield in fact slightly less band width than does a single transformer. This effect may be understood by referring to the ideal terminating impedance characteristic shown in Figure 2 by curves 24 and 26. The first transformer applied to the series resonant antenna has the effect of inverting the input impedance characteristic, that is, the impedance looking into the first transformer or terminating the second transformer, will then be inductively reactive below resonance and capacitatively reactive above, just the reverse to that required. Consequently, the second of the two transformers works into an impedance that is even more unfavorable than that faced by the first, with the result that the gain attained by making the transformation in two steps is cancelled out by the adverse conditions under which the transformation must work. Unless the antenna is intrinsically broad band to begin with there is little to be gained by cascading quarter wave geometric mean transformers.

Thus, it will be noted that the commonly used quarter wave geometric mean transformer has two serious limitations:

1. The impedance characteristics of the antenna are likely to be such that a single transformer will yield only a comparatively modest band width.

2. The impedance characteristics of the antenna are usually such that the band width cannot be appreciably increased by cascading transformers.

As far as the general problem of broad banding an antenna is concerned, there is no particular point in using a quarter matching section at all. That is, the quarter wave matching transformer, as pointed out above, provides a perfect match only at the one frequency for which the system is designed where as for broad-band operation an approximate match such that the standing wave ratio on the feed line is less than some specified value over the desired range of frequencies is better than a low value of standing wave ratio at one particular frequency and higher standing wave ratio characteristics over the rest of the band.

If an antenna is to be matched to less than a S:1 standing wave ratio, where S is some specified value, to a line of characteristic impedance, Z_0, its matched impedance must be capable of representation in the complex impedance plane by points lying within the S:1 standing wave ratio circle of a Z_0 ohm transmission line.

Confining ourselves to loss-less lines, this circle of matching has its center on the R-axis of the complex impedance plane at:

$$C=\frac{Z_0(S^2+1)}{2S} \tag{1}$$

and the radius of the circle of matching is given by the equation:

$$r=Z_0\frac{(S^2-1)}{2S} \tag{2}$$

Further, each circle cuts the resistance axis at the two points

$$R_{min}=\frac{Z_0}{S} \tag{3}$$

and

$$R_{max}=Z_0S \tag{4}$$

These values represent the lower and upper extremes of resistance which satisfy the standard of matching.

If an antenna is to be matched to less than S:1 standing wave ratio on a Z_0 ohm line by means of a series transformer of characteristic impedance Z_m and if it is assumed that the impedance level or resonant resistance R_0 of the antenna is greater than Z_0 so that the match is in a downward direction, then the impedance of the antenna over the range of matching must be representable by points in the complex impedance plane lying on or within the S_m:1 standing wave ratio circle of the line Z_m where S_m and Z_m are related to S and Z_0 by the expression

$$S_m=\left(\frac{Z_m}{Z_0}\right)S \tag{5}$$

This expression, it will be noted, is the condition for common tangency of the circle of matching (S:1, Z_0 ohms) and the latter circle, called the limiting circle, at $R_{min.}$ The limiting circle has its center on the resistance axis at

$$C_m=\frac{Z_m(S_m^2+1)}{2S_m} \tag{6}$$

and a radius

$$r_m=\frac{Z_m(S_m^2-1)}{2S_m} \tag{7}$$

The condition quoted above, namely, that the antenna impedance lies within the limiting circle and that the limiting circle and the matching circle be internally tangent at the smallest resistance satisfying the condition of matching, is merely the necessary condition which must be satisfied if the antenna is to be matched to the given standard by the given transformer. The portions of the antenna's impedance curve which lie outside of the limiting circle of a transformer of characteristic impedance Z_m cannot possibly be matched to the desired standard by means of that transformer. However, the mere fact that the necessary condition for matching is satisfied over a given range of frequencies does not imply that the match can actually be realized.

It will be evident from the above given equation for the radius of the limiting circle that the larger S_m the larger the circle will be. It is further evident from the relation 5 that for a given standard of matching the greater the value of Z_m the greater the value of S_m becomes. Thus, the greater the characteristic impedance of the transformer the larger will be its limiting circle in the complex impedance plane and the greater the range of absolute impedance values satisfying the necessary condition for a broad-band match. Therefore, a transformer of characteristic impedance higher than the geometric mean could be used to advantage. As an example, consider the case of matching the antenna shown in Figure 1, whose characteristics are shown in Figure 2, to a less than 2:1 standing wave ratio on a 50 ohm line. The antenna impedance is plotted on the complex impedance in Figure 4, in which the resistance in ohms is plotted as abscissa and reactance in ohms as ordinates and on which the frequencies corresponding to the various impedance points are indicated by marked points along curve **42**. The smallest circle **40**, on this diagram is the circle of matching and it is evident at a glance that only the small frequency range extending from 284 to 296 megacycles per second is initially matched to the stated (2:1 standing wave ratio on a 50 ohm line) standard. Circle **44** is the limiting or 2.92:1 standing wave ratio circle of a conventional geometric mean transformer. Obviously only the frequency range from about 251 to 350 megacycles

per second can possibly be matched by the geometric mean transformer. The largest circle **46** is the limiting or 4:1 standing wave ratio circle of a 100 ohm transformer. It is evident that this circle includes almost the entire range of frequencies covered by the measurements and that, therefore, a 100 ohm transformer is capable of much greater band width with the given antenna than is the conventional matching section. It is possible that the antenna can be matched within the required standards from 230 megacycles to over 426 megacycles by the 100 ohm transformer.

However, one must take care not to imply from this, that the higher the characteristic impedance of the matching section, the better. On the contrary, if band widths equivalent to or of the order of one frequency octave are sought, there is a definite upper limit to the optimum impedance of the transformer. This optimum value is determined by the impedance level of the antenna and by the standards of matching according to the following considerations.

The primary factors governing the choice of antenna impedance level and the characteristic impedance of the matching section in matching antennas over frequency ranges of 2:1 or more will now be considered. It is desirable that some part of the impedance range be matched to begin with and that this match be independent of the length of the matching section. It is preferable that the permanently matched region lie somewhere near midband for then it is possible to choose values of the electrical length of the transformer to match the end portions of the band without thus mismatching the center portion of the band due to an unfortunate choice in the electrical length. This may be accomplished by choosing Z_m and R_0 in relation to Z_0 and S in such manner that part of the original antenna impedance curve which initially lies within the S:1 circle of the Z_0 ohm line cannot possibly be transposed by the transformer Z_m to lie outside the circle, no matter what the electrical length of the transformer.

Thus, suppose it is desired to match an antenna of impedance level R_0, greater than Z_0, to less than S:1 standing wave ratio on the line Z_0 by means of a transformer of impedance Z_m which is also greater than Z_0. It is evident from an inspection of the curves in Figure 4 or from Equation (4) that SZ_0 is largest resistance included within the S:1 standing wave ratio circle of a Z_0 ohm line. Furthermore, this maximum value of resistance SZ_0 lies on the

$$\frac{SZ_0}{S_m}:1$$

standing wave ratio circle, or on the

$$\frac{Z_m}{SZ_0}:1$$

standing wave ratio circle, of the line Z_m, depending upon whether Z_m is greater or less than Z_0. It is the relation of R_0 to the Z_m circles which determines whether the match over the mid frequency portion of the antenna impedance curve is dependent on or independent of the electrical length of the transformer. Since R_0 can lie below or above or within the Z_m circle and there are two possible Z_m circles depending upon whether Z_m is greater or less than SZ_0, it is evident that there are a total of six possible combinations of values of R_0 and Z_m to consider.

If Z_m is greater than SZ_0 and R_0 is greater than

Z_0 the maximum resistance within the S:1 standing wave ratio circle of a Z_0 ohm line, that is, SZ_0 ohms, lies on the

$$\frac{Z_m}{SZ_0}:1$$

standing wave ratio circle of a Z_m ohm line, which latter circle includes resistances ranging from a minimum of SZ_0 to a maximum of

$$\frac{Z_m^2}{SZ_0}$$

Whether R_0 is matched to begin with, or whether it can be matched by the transformer Z_m, depends upon the relation of R_0 to this range of resistance values, or, in other words, depends upon whether R_0 lies below, above, or within the

$$\frac{Z_m}{SZ_0}:1$$

standing wave ratio circle of the line Z_m. There are three possibilities:

1. R_0 less than SZ_0 ohms: The antenna is matched at mid-band initially, but can be mismatched if the electrical length of the transformer is unfortunate, that is, R_0 can be transformed to lie outside the circle of matching if the transformer length is improper.

2. R_0 more than

$$\frac{Z_m^2}{SZ_0}$$

ohms: The antenna is mismatched initially and can be matched by the transformer only if its electrical length falls in a certain critical range.

3. R_0 between SZ_0 and

$$\frac{Z_m^2}{SZ_0}$$

ohms: The antenna is mismatched initially and will remain mismatched, since R_0 lies within the

$$\frac{Z_m}{SZ_0}:1$$

standing wave ratio circle of the line Z_m, which circle is entirely exterior to the S:1 standing wave ratio circle of the line Z_0.

If Z_m is less than SZ_0, R_0 greater than Z_0, the maximum resistance within the S:1 standing wave ratio circle of the line Z_0, namely SZ_0 ohms, lies on the

$$\frac{SZ_0}{Z_m}:1$$

standing wave ratio circle on the line Z_m, which latter circle includes resistances ranging from a minimum of

$$\frac{Z_m^2}{SZ_0}$$

to a maximum of SZ_0 ohms. Whether R_0 is matched initially, whether it can be matched, or whether it will continue to be matched depends upon its position with respect to this circle. Again there are three possibilities:

1. R_0 less than

$$\frac{Z_m^2}{SZ_0}$$

ohms: The antenna is matched at mid-band initially, but can be mismatched if the length of the transformer is such as to transform R_0 outside the S:1 standing wave ratio circle of the line Z_0.

2. R_0 more than SZ_0 ohms: The antenna is mismatched initially, but can be matched if the length of the transformer is favorably chosen,

that is, if the transformer is of proper length to transpose R_0 into the circle of matching.

3. R_0 between

$$\frac{Z_m^2}{SZ_0}$$

and SZ_0 ohms: The antenna is matched at mid-band initially and cannot be mismatched by the transformer Z_m, since R_0 lies within the

$$\frac{SZ_0}{Z_m}:1$$

standing wave ratio circle of the line Z_m and since that circle is entirely contained within the circle of matching.

Evidently it is only the last of these possible combinations of ranges of R_0 and Z_m values which permits an absolutely free choice of the electrical length of the transformer, so that a transformer length may be chosen so as to match the two-end portions of the band without the necessity of precautions being taken to avoid incurring a mid-band mismatch. The conditions imposed on R_0 and Z_m, if really wide band widths with less than S:1 standing wave ratio on a line of impedance Z_0 are to be attained with a transformer of characteristic impedance Z_m, are, therefore:

1. That the characteristic impedance Z_m of the transformer be more than Z_0 but no more than SZ_0 ohms, and

2. That the resonance impedance, or impedance level, of the antenna be more than

$$\frac{Z_m^2}{SZ_0}$$

but no more than SZ_0 ohms. However, it was previously shown that there was a definite advantage gained in using a transformer of high characteristic impedance. Applying this principle, the above conditions become:

For optimum band width with less than S:1 standing wave ratio on a line of characteristic impedance Z_0 from a series-resonant antenna in conjunction with a series-transformer matching section, both the characteristic impedance of the transformer and the impedance level of the antenna should be equal, approximately, to SZ_0 ohms.

Let us apply the conditions developed above to the problem of matching the antenna of Figures 2 and 4 to less than 2:1 standing wave ratio on a 50 ohm line. The antenna's impedance level is 106 ohms, which is close enough to 2×50 or 100 ohms to satisfy the second condition; the first condition is satisfied by using a transformer of characteristic impedance 100 ohms. The absolute antenna impedance curve of Figure 4 has been replotted, in terms of impedance relative to 100 ohms in Figure 5 on a rectangular form of a standard transmission line chart. The limiting circle **50** for this particular case, that is the 4:1 standing wave ratio circle of the 100 ohm line, has been emphasized to indicate clearly the range over which the antenna's impedance characteristic satisfies the necessary condition for matching by this transformer. It is evident that almost the entire range of data plotted along line **52** satisfies this condition and that the antenna may, but not necessarily can, be matched all the way from about 239 to about 438 megacycles. The matching circle; that is, the 2:1 standing wave ratio circle **40** of a 50 ohm line, is drawn in to aid in selecting the most favorable value of the electrical length of the transformer. The procedure in choosing the most favorable electrical length is as follows:

1. Consider the two extreme impedance points lying within the limiting circle, that is, the 249 and 426 megacycle points in curve 52.

2. Referring to the circles of constant electrical length, which are labelled with the value of the electrical length in quarter wavelengths, it is evident that the low frequency extreme, the 249 megacycle point, lies on the 2.7:1 standing wave ratio circle at 0.48 (read along the scale along the outer edge of circle 50) and that this standing wave ratio circle intersects the circle of matching 40 at 0.20 and 1.80 respectively. It follows therefore that any value of the electrical length of the 100 ohm transformer lying between (0.48—0.20) and (0.48+0.20) quarter wavelength at 240 megacycles per second will cause the low frequency extreme to be matched. That is, any electrical length between 0.28 and 0.68 quarter wavelength will match the 249 megacycle per second point.

3. Similarly, the high frequency extreme, the 426 megacycle point, lies on the 3.8:1 standing wave ratio circle at about 0.99 (on the scale along the outer edge of circle 50); the 3.8:1 standing wave ratio circle intersects the circle of matching 40 at 0.05 and 1.95, respectively. Therefore, any transformer length included in the range (0.99—0.05) and (0.99+0.05) quarter wavelengths at 426 megacycles per second will match the high frequency end of the band. That is to say, at 426 megacycles the electrical length of the transformer should be somewhere between 0.94 and 1.04 quarter wavelengths.

4. It remains to pick a value of the electrical length which falls within both the high and low frequency ranges. Evidently an electrical length of 0.94 quarter wavelengths at 426 megacycles corresponds to (249/426)0.94 or 0.55 quarter wavelength at 249 megacycles, a value lying within the low frequency range. Similarly, an electrical length of 1.04 quarter wavelengths at 426 megacycles corresponds to 0.61 quarter wavelengths at 249 megacycles per second, a value also lying within the permitted low frequency range. Hence any electrical length between 0.94 and 1.04 quarter wavelengths at the high end of the band will cause both extreme ends to be matched.

5. Choosing a value toward the lower limit of this range, say 0.97 at 426 megacycles per second, in order to favor the low frequency end of the band where more band width is to be gained since the 249 megacycles per second point lies farther inside the limiting circle than does the 426 megacycle per second point, it is easily shown that the entire range extending from 243 to 426 megacycles per second can be matched.

An electrical length of 0.97 quarter wavelengths at 426 megacycles corresponds to an electrical length of 0.70 quarter wavelengths or 63 degrees, at 306 megacycles, the resonant frequency of the antenna. Evidently the high impedance transformer is much shorter than the conventional quarter wave transformer of present antenna practice.

The advantage of a high impedance, less than quarter wave transformer over the conventional geometric means, quarter wave matching section may be judged from Figure 6, in which standing wave ratio frequency characteristics for the original antenna, curve 61; the antenna matched by a conventional quarter wave geometric mean transformer, curve 63; and the antenna matched by the broad-band transformer designed above, curve 65; are plotted for comparison. It is evident that the 100 ohm, 63 degree transformer yields more than twice as much band width as the conventional 73 ohm, 90 degree transformer which would ordinarily be used with the given antenna.

It is evident that if full advantage is to be taken of the principle outlined above, some control over the value of the impedance level of the antenna to be matched is desirable. While such control is not always possible, there are a great many types of antenna installations in which it is available. Among these are simple stubs and dipoles mounted in directive systems and on curved surfaces, the latter being a common occurrence in aircraft radio, and stubs and dipoles of the so-called "sleeve" type shown in Figure 1 in which practically any desired impedance level can be obtained simply by feeding the antenna at the proper point relative to its current distribution.

While I have illustrated a particular embodiment of the present invention, it should be clearly understood that it is not limited thereto since many modifications may be made in the several elements employed and in their arrangement and it is therefore contemplated by the appended claims to cover any such modifications as fall within the spirit and scope of the invention.

What is claimed is:

1. A broad-band antenna system including a vertical quarter wave radiator, a transmission line for coupling said radiator to a source of high frequency energy and an impedance matching section interposed between said radiator and said transmission line, said section having a length of the order of one quarter wavelength near the high frequency end of said band and a characteristic impedance substantially greater than the geometric mean between the impedance of the radiator and the transmission line.

2. A broad-band antenna system including a vertical quarter wave radiator, a transmission line for coupling said radiator to a source of high frequency energy and an impedance matching section interposed between said radiator and said transmission line, said section having a length of substantially less than one quarter wavelength near mid-frequency of the band and a characteristic impedance substantially greater than the geometric mean between the impedance of the radiator and the transmission line.

3. A broad-band antenna system including a radiator member, a transmission line for coupling said radiator to a source of high frequency energy and an impedance matching section interposed between said radiator and said transmission line, said section having a length of substantially less than one quarter wavelength near mid-frequency of the band and a characteristic impedance substantially greater than the geometric mean between the impedance of the radiator and the transmission line.

4. A broad-band antenna system including a radiator member having a high input impedance, a transmission line for coupling said radiator to a source of high frequency energy and an impedance matching section interposed between the input of said radiator and said transmission line, said section having a length of substantially less than one quarter wavelength near mid-frequency of the band and a characteristic impedance substantially greater than the geometric mean between the impedance of the radiator and the transmission line.

5. A broad-band antenna system including a

radiator, a transmission line for coupling said antenna to a high frequency energy transducer means and a series impedance matching section interposed between the feed point of said antenna and said transmission line, said section having a length shorter than one quarter of a wavelength near the high frequency end of said band and a characteristic impedance substantially greater than the geometric mean between the impedance of said antenna and said transmission line.

6. A broad-band antenna system including a radiator, a transmission line for coupling said antenna to a high frequency energy transducer means and a series impedance matching section interposed between the feed point of said antenna and said transmission line, said section having a length of substantially less than one quarter wavelength near mid-frequency of the band and a characteristic impedance substantially greater than the geometric mean between the impedance of said antenna and said transmission line.

7. In a broad-band antenna system including a vertical quarter wave radiator, a transmission line for coupling said antenna to high frequency energy transducer means, said antenna having a feed point at which the antenna presents a higher input impedance than the impedance of said transmission line, a series impedance matching section interposed between said antenna feed point and said transmission line, said section having a length substantially less than one quarter of a wavelength at the mid band frequency and a characteristic impedance substantially equal to the impedance of the feed point of said antenna.

8. In a broad-band antenna system including a radiator and a transmission line for coupling said antenna to high frequency energy transducer means, means for matching said antenna to said transmission line over a broad-band of frequencies with less than a S:1 standing wave ratio where S is any chosen number greater than unity, the impedance of said transmission line being Z_0 ohms, the impedance of said antenna being Z_a ohms, the impedance of said matching section being Z_m, the impedance of said antenna being not less than

$$\frac{Z_m^2}{SZ_0}$$

ohms but not significantly more than SZ_0 ohms where Z_{m2} is substantially greater than Z_aZ_0.

9. In a broad-band antenna system including a radiator having a high input impedance and a transmission line for coupling said antenna to a source of high frequency energy, a wide banding section interposed between said antenna and said transmission line, said section having a length substantially less than one quarter wavelength at mid-band frequency and a characteristic impedance substantially greater than the geometric mean between the resonant impedance of the antenna and the characteristic impedance of the transmission line.

10. A broad-band antenna system including a radiator, a transmission line for coupling said antenna to a high frequency energy transducer means and a series matching section interposed between the feed point of said antenna and said transmission line, said section having a length shorter than one quarter of any wavelength within said band and a characteristic impedance substantially greater than the geometric mean between the impedance of said antenna and said transmission line.

11. In a broad-band antenna system including a radiator, a transmission line for coupling said antenna to a high frequency energy transducer means, a series matching section interposed between the feed point of said antenna and said transmission line, said section having a length shorter than one quarter of any wavelength within said band and a characteristic impedance substantially greater than the geometric mean between the impedance of said transmission line and that of said antenna and approaching that of said antenna.

12. In a broad-band antenna system including a vertical quarter wave radiator and a transmission line for coupling said antenna to high frequency energy transducer means, said antenna having a feed point near the center of said radiator, a series matching section interposed between said antenna feed point and said transmission line, said section having a length shorter than one quarter of any wavelength within said band and a characteristic impedance substantially higher than the geometric mean of the impedance of said transmission line and of said antenna and of the order of the resonant or mid-band impedance of the feed point of said antenna.

13. In a broad-band antenna system including a vertical quarter wave radiator and transmission line for coupling said antenna to high frequency energy transducer means, said antenna having a feed point near the center of said radiator, a series matching section interposed between said antenna feed point and said transmission line, said section having a length shorter than one quarter of any wavelength within said band and a characteristic impedance substantially higher than the geometric mean of the impedance of said transmission line and of said antenna and being of the order of the impedance of the feed point of said antenna.

14. In a broad-band antenna system including a radiator and a transmission line for coupling said antenna to high frequency energy transducer means, means for matching said antenna to said transmission line over a broad-band of frequencies with less than a S:1 standing wave ratio where S is a chosen number greater than unity, the impedance of said transmission line being Z_0 ohms, the impedance of said antenna being Z_a ohms, the impedance of said matching section being Z_m, the impedance of said antenna lying between the limits set by the expressions

$$\frac{Z_m^2}{SZ_0}$$

and SZ_0 and the impedance of the matching section Z_m lying between the limits $(Z_aZ_0)\,\frac{1}{2}$ and SZ_0 ohms.

15. In combination with broad-band antenna system including a radiator having a sleeve portion extending from a conductive ground plane and a concentric extending rod portion, means for exciting said radiator connected between the adjacent ends of said sleeve and rod portion including a series matching section and a coaxial transmission line, the relative lengths of said sleeve and said extending rod portion being so chosen as to present a high driving impedance and said series matching section having a characteristic impedance greater than the geometric mean of the driving impedance of said antenna and the impedance of said transmission line.

16. In a broad-band antenna system including a radiator having a sleeve portion extending from a conductive ground plane and a concentric extend-

ing rod portion, means for exciting said radiator connected between the adjacent ends of said sleeve and rod portion including a series matching section and a coaxial transmission line, the relative lengths of said sleeve and said extending rod portion being so chosen as to present a high driving impedance, said series matching section having a characteristic impedance greater than the geometric mean of the driving impedance of said antenna and the impedance of said transmission line, said matching section impedance approaching the driving point impedance of said antenna.

17. In a broad-band antenna system including a radiator having a sleeve portion extending from a conductive ground plane and a concentric extending rod portion, means for exciting said radiator connected between the adjacent ends of said sleeve and rod portion including a series matching section and a coaxial transmission line, the relative lengths of said sleeve and said extending rod portion being so chosen as to present a high driving impedance and said series matching section having a characteristic impedance greater than the geometric mean of the driving impedance of said antenna and the impedance of said transmission line, said matching section impedance approaching but not exceeding the driving point impedance of said antenna.

18. A broad-band antenna system including a vertical quarter wave radiator, a transmission line for coupling said radiator to a source of high frequency energy and an impedance matching section between said radiator and said transmission line, said section being so dimensioned as

to introduce into said transmission line reflections which tend to cancel reflections of energy from said radiator into said transmission line over a wide band of frequencies.

19. A broad-band antenna system including a radiator member having a high input impedance, a transmission line for coupling said radiator to a source of high frequency energy and an impedance matching section interposed between the input of said radiator and said transmission line, said section having a length substantially less than one quarter wave length near the mid-frequency of the band and a characteristic impedance substantially greater than the geometric mean between the impedance of the radiator and the transmission line, whereby said matching section introduces into said transmission line reflections of such magnitude and phase as to cancel reflections of energy into said transmission line from said radiator over a wide band of frequencies.

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