

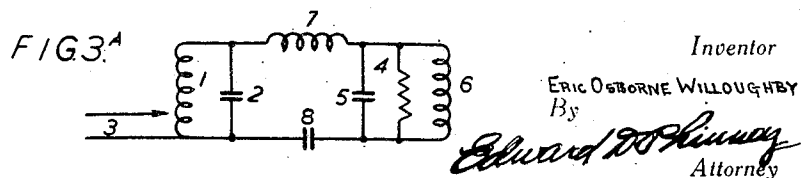
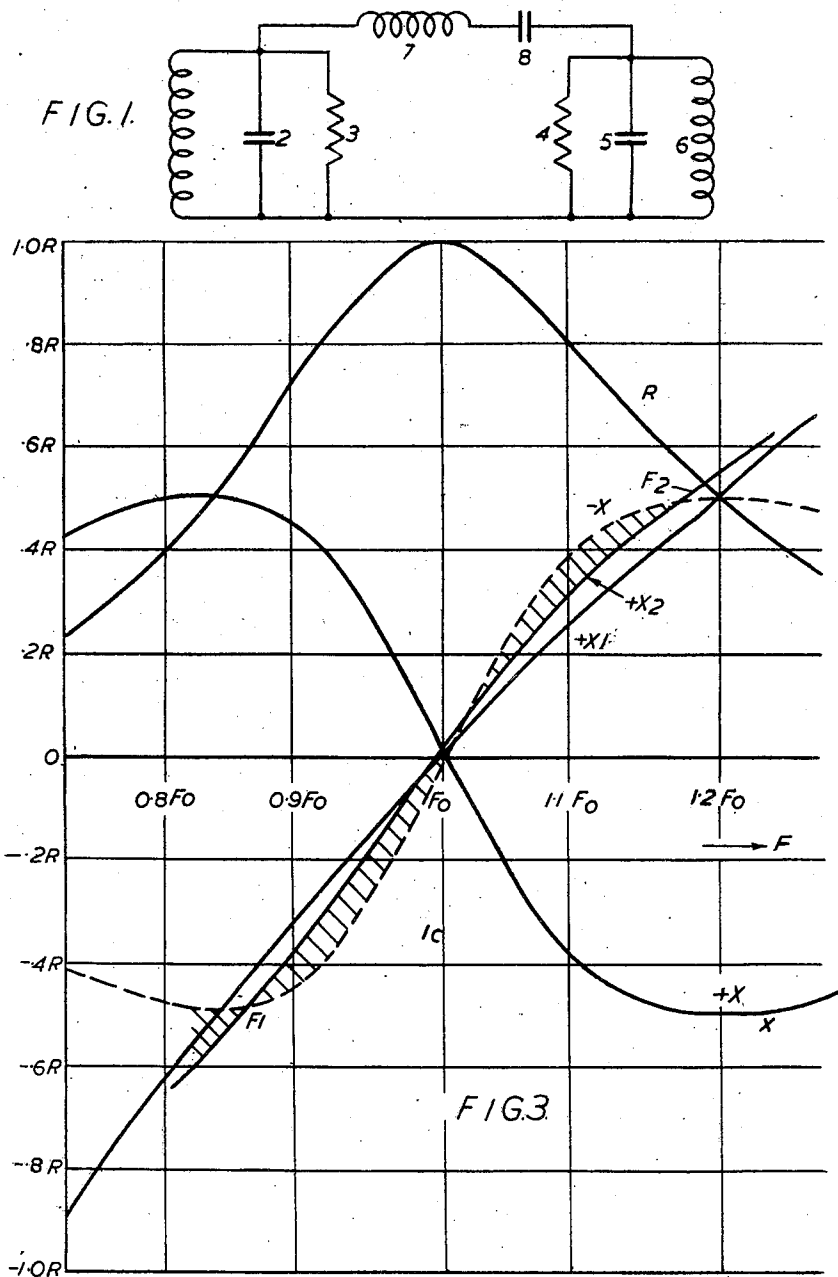
June 27, 1950

E. O. WILLOUGHBY
ARRANGEMENT FOR COUPLING WIDE FREQUENCY BAND
ANTENNAE TO TRANSMISSION LINES

2,512,704

Filed Jan. 16, 1945

3 Sheets-Sheet 1



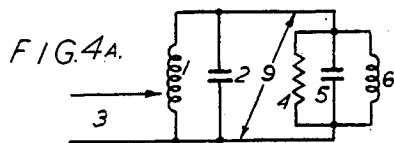
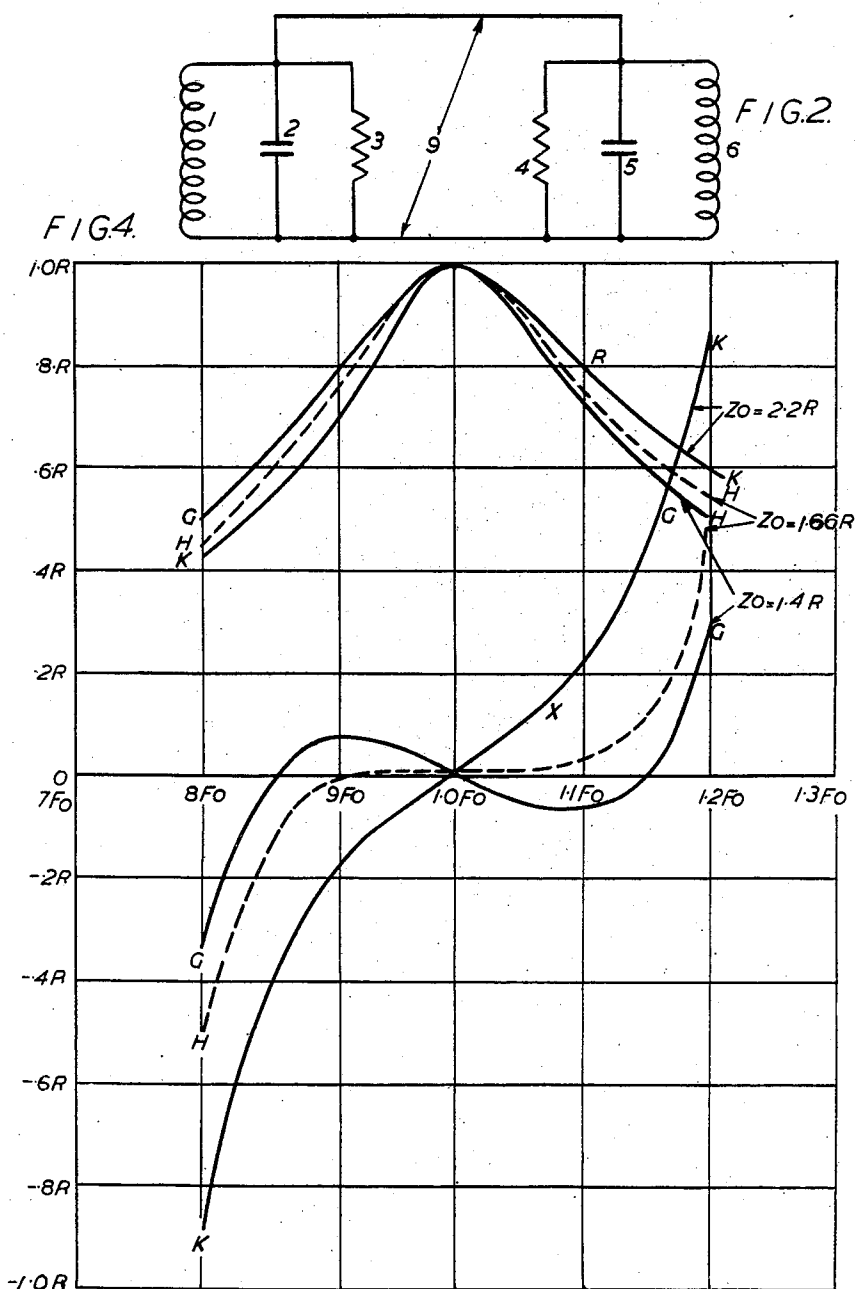
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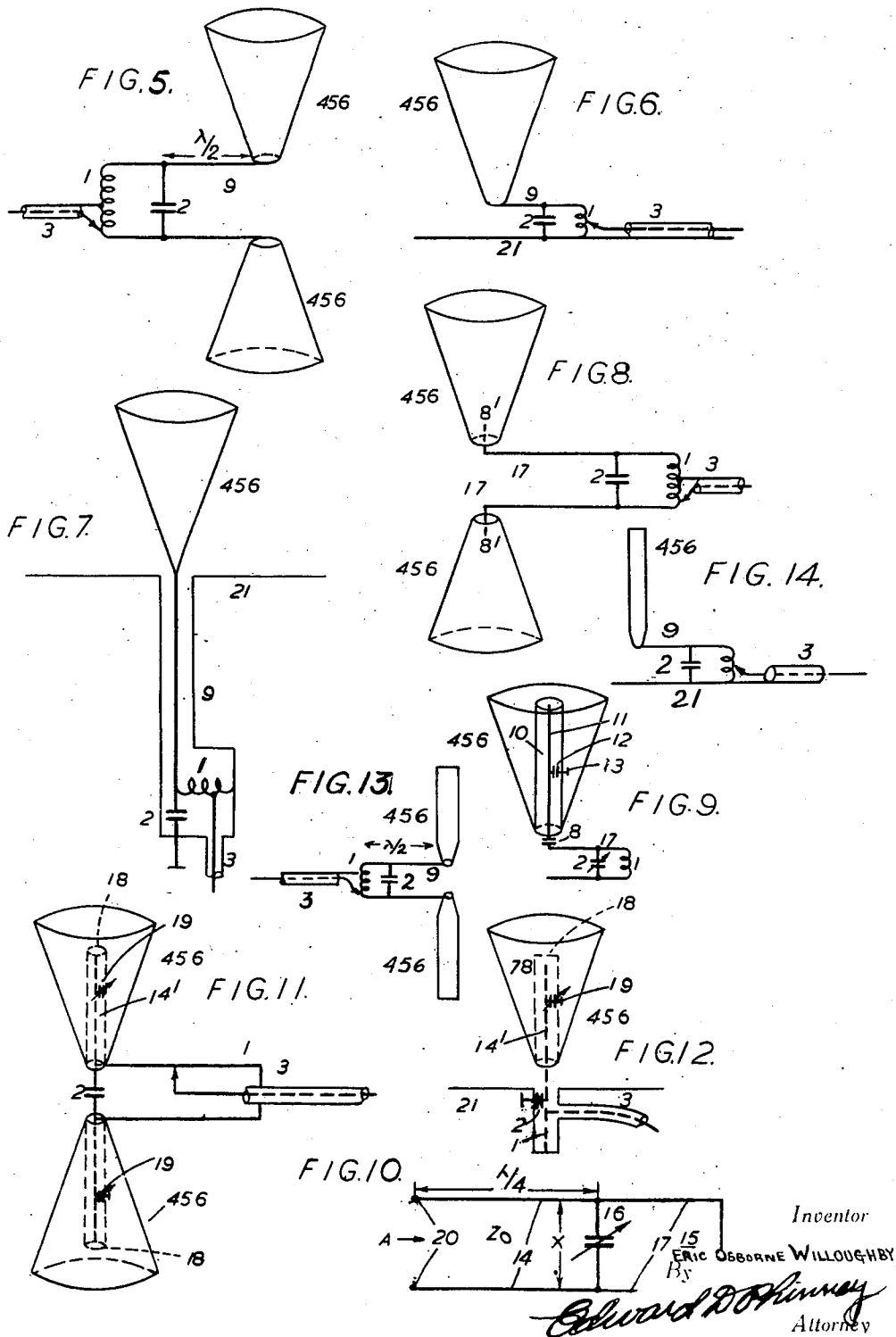
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3 Sheets-Sheet 3



UNITED STATES PATENT OFFICE

2,512,704

ARRANGEMENT FOR COUPLING WIDE FREQUENCY BAND ANTENNAE TO TRANSMISSION LINES

Eric Osborne Willoughby, London, England, assignor, by mesne assignments, to International Standard Electric Corporation, New York, N. Y., a corporation of Delaware

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Patent expires December 6, 1963

3 Claims. (Cl. 250—33)

1

The present invention relates to arrangements for coupling antennae to transmission lines and it has for its object to provide such arrangements which have a low degree of overall mismatch between the impedances of the arrangements throughout a broad band of ultra high frequencies, for example, of the order of $\pm 20\%$ of the mean operating frequency, which may be for example, of the order 100 to 150 megacycles per second.

The arrangements according to this invention may be used for transmission or reception of broad frequency bands in the ultra high frequency range, for example in the art of television, radio location equipment utilising frequency sweep methods or for systems utilising the transmission and reception of pulses.

According to the invention arrangements of the type specified having a low degree of overall mismatch between the impedances throughout a broad band of ultra high frequencies comprise an end fed type antenna half wave resonant at substantially the mean operating frequency of the band or a dipole antenna having each element half wave resonant substantially at said mean operating frequency, a transmission line for coupling said antenna to a translation device, means for forming a combination with said transmission line a parallel tuned circuit resonant at substantially said mean operating frequency and a series tuned circuit resonant at substantially said mean operating frequency coupling said antenna to said parallel tuned circuit, said parallel tuned circuit being so formed as to have substantially the same "Q" as the antenna and the peak resistance of said parallel circuit at the point of coupling to said series tuned circuit substantially equal to the peak resistance of the antenna at the point of coupling to said series tuned circuit so as to obtain substantial cancellation or neutralisation of the sum of the reactances due to the antenna and parallel tuned circuit.

In a slight modification of the invention, the series tuned circuit may be replaced by a portion of transmission line half wave resonant substantially at the mean operating frequency connecting the antenna to the parallel tuned circuit, and having such impedance characteristic as substantially to neutralise the reactances of the parallel tuned circuit and antenna over the operating band of frequencies.

The physical length of the antenna should not be artificially shortened by the use of loading coils or end capacity, since these means in general reduce the band width of the antenna by main-

2

taining the magnitude of the reactive constants and at the same time reducing the damping. The resistance and reactance of end fed antennae are relatively high and these factors are only sufficiently low for cases where practical constants are possible for the compensating series tuned circuit, in antennae of low characteristic impedance, for example, conical antennae.

The invention and the principles on which it is based will be made clearer in the following description which also includes a description of several preferred embodiments of the invention which are given by way of example only. Reference will be made to the accompanying drawings in which:

Figs. 1 and 2 are diagrammatic circuit arrangements which illustrate the principles on which the invention is based;

Fig. 3 shows various characteristic curves of the arrangement shown in Fig. 1 or Fig. 3A which is an alternative form of representing the circuit shown in Fig. 1;

Fig. 4 shows various characteristic curves of the arrangement shown in Fig. 2 or Fig. 4A;

Figs. 5 to 9 inclusive illustrate several practical embodiments of the invention;

Fig. 10 is a diagram used in the explanation of

Figs. 11 and 12 which illustrate further embodiments of the invention;

Figs. 13 and 14 illustrate several practical embodiments of the invention.

In Fig. 1 of the drawings, the parallel tuned circuits 1, 2, 3 and 4, 5, 6 have equal "Q," that is ratio of reactance to resistance, and equal maximum equivalent shunt resistances, represented by resistances 3 and 4 respectively. These two parallel tuned circuits, resonant at the mean operating frequency of the desired frequency band are connected together by means of the series tuned circuit 7 and 8 resonant at said mean operating frequency, the inductance 7 and capacity 8 being appropriately chosen. The action of these three circuits will be explained with reference to Fig. 3. As shown in Fig. 3A, the capacity 8 may be placed in one lead and the inductance 7 in the other.

In Fig. 3, the ordinates represent resistance or reactance and the abscissae represent frequencies in terms of the mean frequency F_0 . The curves R and X represent the variation of resistance and reactance respectively of a parallel tuned circuit resonant at the mean frequency F_0 , through which point of the abscissae axis the curve X passes. The "Q" of the parallel tuned

circuit in the case of the curves shown in Fig. 3 is 2.5. The curves indicated at X1 and X2 represent the reactance characteristic curves of two different series tuned circuits. The circuit having the characteristic X1 gives quite a good reactance compensation or neutralisation with the parallel tuned circuit whose reactance characteristic is X. This can be seen from the fact that the two curves X1 and X are on opposite sides of zero reactance and have substantially equal but opposite slopes. However, the series circuit having a reactance characteristic X2 gives a still better reactance neutralisation of the reactance of the circuit whose characteristic is X. The series circuit having the characteristic X2 has larger series reactances than the series circuit having the characteristic X1 and the uncompensated or unneutralised reactances (X2-X) which remain in the combined parallel and series tuned circuit are shown shaded in Fig. 3 (the curve X having been reversed as shown in the broken line).

In regard to Fig. 3 it should be observed that since there are two parallel tuned circuits each having impedances represented by $R+jX$ connected by a series tuned circuit, the series reactance curves should be doubled in ordinates to represent the complete reactance compensation by the series tuned circuit. More precisely, a reactance characteristic of the type shown at x, Fig. 3, should be added to x to represent the sum of the characteristics of the antenna and parallel tuned circuit across the transmission line 3. This implies that the reactances comprising the series tuned circuits whose characteristics are X1 and X2, Fig. 3, should have their ordinates approximately doubled, and the ordinates differences (X2-X) of the shaded areas representing unneutralised reactances will also be doubled.

If there are two parallel circuits each having reactance characteristics of the type shown at X, that is they both have equal "Q" and each have a resistance characteristic such as R, of equal maximum value, the reactances of the series tuned circuit and the input parallel tuned circuit, and the reactances of the series tuned circuit and the output parallel tuned circuit very nearly neutralise each other and the resistances of the two parallel circuits are substantially equal, so that throughout the frequency range represented by the abscissae of the points F1, F2 in Fig. 3, the mismatch between the impedances of the two parallel circuits is represented by that due to the unneutralised reactances indicated by the ordinates of shaded areas in Fig. 3, which mismatch is very low throughout the frequency range F1 to F2.

In other words, to a first approximation and neglecting the slight asymmetry of the parallel circuit characteristics about the mean operating frequency, or resonant frequency due to its low "Q," if the reactances 1, 2, 5 and 6 are each of magnitude X_p and the reactances 7, 8 are each of magnitude X_s , resistance 4 is R ohms and the transmission line 3 is tapped on the inductance 1 so as to produce the same "Q" for the parallel circuit on the left as the one on the right (Fig. 3) of the series tuned compensating circuit 7, 8 and if substantially

$$X_p = R/Q \text{ and } X_s = QR$$

then reactance cancellation or neutralisation at the frequencies near the peaks of the reactance characteristics of the parallel tuned circuits will occur.

A length of transmission line halfwave resonant at the mean operating frequency will match any two equal impedances at the mean operating frequency, but it is possible by appropriate choice of characteristic impedance of the transmission line to obtain over a frequency band good resistance matching and some degree of reactance cancellation but not so good as the series tuned coupling circuit.

Consider a transmission line of length l with the frequency increasing from below the mean value to above the mean frequency, the length of the line thus varying from above $\lambda/2$ to below $\lambda/2$ where λ is the mean operating wave length, and find the characteristic impedance Z_0 so that an impedance $R+jx$ at its output terminals appears to be of magnitude $R-jx$ at the input terminals: i. e.

$$R+jx = Z_0 \frac{(R-jx) \cos \frac{2\pi l}{\lambda} + jZ_0 \sin \frac{2\pi l}{\lambda}}{Z_0 \cos \frac{2\pi l}{\lambda} + j(R-jx) \sin \frac{2\pi l}{\lambda}} \quad (1)$$

Solving—this has only one real solution

$$Z_0 = X \cot \frac{2\pi l}{\lambda} + \sqrt{X \operatorname{cosec}^2 \left(\frac{2\pi l}{\lambda} \right) + R^2} \quad (2)$$

Fig. 2 shows diagrammatically two equal impedances, parallel tuned circuits 1, 2, 3, 4, 5, 6 connected by a length of transmission line 9 and Fig. 4 shows in three sets of curves labelled G, H, K the results of viewing the impedance of Fig. 2 (i. e. a parallel tuned circuit of peak resistance R and Q=2.5) through the half wave resonant transmission line 9 at mean mean operating frequency f_0 for different impedances Z_0 of the line 9 equal to 1.4R, 1.66R and 2.2R. It will be observed by comparing G, H, K, Fig. 4, with X, Fig. 3, that while $Z_0=1.66R$ (curves H, Fig. 4) gives reactance compensation at the peaks of the reactance curve (i. e. at frequencies $0.8F_0$ and $1.2F_0$) and reasonable resistance matching (curves K, Fig. 4, and R, Fig. 3), the characteristics K (Fig. 4) with $Z_0=2.2R$ gives much better average reactance cancellation than either of the lower characteristic impedance connecting portions of transmission lines having curves H and K as well as giving good resistance matching.

In order to determine the best characteristic impedance Z_0 for the half wave transmission line one may work out the optimum values of Z_0 for several frequencies in the operating band. This will differ from frequency to frequency and a value may be finally selected above the mean which provides reasonable average reactance compensation of the reactances of the antenna and the parallel tuned circuit when the half wave transmission line of appropriate Z_0 is connected to the parallel tuned circuit.

The resistance and reactance characteristics of a low impedance antenna near resonance are, apart from slight asymmetry, closely analogous to the corresponding characteristics of a parallel tuned circuit, in the frequency range corresponding to the range between the peaks of the reactance-frequency characteristic. In general, therefore, low impedance antennae are the best for carrying out the invention and the characteristic impedance of the antenna must be sufficiently low if use is to be made of practical circuit constants in forming the compensating circuits, i. e. transmission line elements of practicable realisable characteristic impedance. An expedient will be described hereinafter, however.

which will enable antennae of higher characteristic impedance and radiation resistance to be used, without impracticably large values of the compensating circuit elements.

The antenna takes the place of the parallel tuned circuit 4, 5, 6 and its frequency-reactance characteristic may be made more symmetrical about its resonant frequency by a small amount of series inductance or shunt capacity.

End fed antennae of the half-wave length element type have the appropriate type of impedance characteristic for reactance neutralisation according to this invention. This is either a half wave resonant length vertical antenna above an earth plane, or a dipole of half wave resonant elements. The half wave lengths refer to the mean operating wave length of the desired operating frequency range. The resistance and reactance of antennae of this type are, however, relatively high and only those types of antennae, for example of the conical type, can be used which have sufficiently low characteristic impedance values if practical circuit constants are to be possible for the compensating circuits. A cylindrical vertical antenna having a conical end near the earth plane, or dipoles having adjacent conical ends may be employed, and in this case the overall characteristic impedance of the cylindrical portion should preferably be substantially equal to the characteristic impedance of the conical portion. This embodiment is shown in Figs. 13 and 14.

Referring again to Fig. 1 the parallel tuned circuit 4, 5, 6 represents the end impedance of a half wave antenna and 1, 2 represents a parallel tuned circuit shunted across the input transmission line represented by resistance 3. The circuit 1, 2, 3 is arranged to have substantially the same "Q" as the antenna 4, 5, 6. It will be understood that the circuit 1, 2 includes any stray capacity introduced by the transmission line connection.

As already stated, 7 and 8 is a series tuned circuit coupling the antenna to the parallel tuned circuit 1, 2, 3 terminating the transmission line and the circuits 1, 2, 3, 4, 5, 6, and 7, 8 are all resonant at the mean operating frequency of the desired operating frequency band.

To apply the principles illustrated in Fig. 1 effectively, as already stated the characteristic impedance of the antenna must be low, so that the maximum end radiation resistance is of the order of 300 ohms for the balanced dipole antenna and half this amount for the vertical unbalanced antenna. This is also true for the case of the half wave coupling transmission line 9 illustrated in Fig. 2. The characteristic impedance of 9 becomes impracticably high even for balanced antennae fed by a balanced transmission line if the peak radiation resistance of the antenna exceeds the value given above.

Figure 5 shows a dipole antenna with conical elements 4, 5, 6 each half wave length resonant at the mean operating frequency. 3 is the transmission line and 1, 2 the parallel tuned circuit resonant at the mean operating frequency and 3 is connected at such points on the inductance 1 so as to give to circuit 1, 2, 3 the same shunt peak resistance as that of the antenna and the inductance and capacity 1, 2 are adjusted to give the same Q as that of the antenna. 9 is the half wave length transmission line at the mean operating frequency coupling 1, 2, 3 to 4, 5, 6 as explained with reference to Fig. 2. The characteristic impedance of the antenna 4, 5, 6 is suf-

ficiently low to enable a practical transmission line 9 to be used.

Fig. 6 shows the arrangement of an unbalanced antenna 4, 5, 6 located above the earth plane 21 and is the unbalanced version of the balanced arrangement shown in Fig. 5, utilising an unbalanced transmission line for the half wave portion 9. Fig. 7 shows also the arrangement of an unbalanced antenna but utilising a concentric conductor or coaxial cable as the portion 9.

Fig. 3A shows a slightly modified form of Fig. 1. In Figure 3A the inductance 7 is connected in one lead between the two parallel tuned circuits and the capacity 8 in the other, whereas in Fig. 1 the inductance 7 and capacity 8 are in series in the same lead. In either case the inductance 7 is quite impractical as a lumped reactance at ultra high frequencies and in practice this takes the form of a length of very high impedance transmission line, of the order of one sixth the mean operating wave length and is coupled by capacity to the end of the antenna.

Fig. 8 shows the same antenna as in Fig. 5 but coupled by a series resonant circuit in the form of a length of high impedance transmission line 17 providing the series inductance 7, Fig. 3, coupled to the antenna at its ends by capacity in the form of open stubs formed by the conductors 8' and the interior of the antenna, 4, 5, 6.

So far it has been assumed that the characteristic impedance of the antenna is sufficiently low. In general however owing to the characteristic impedance of the antenna being too high for practical compensation by a single series tuned circuit a portion of transmission line 17 having the necessary high characteristic impedance to provide the necessary inductance for the series tuned circuit may not be practical and it will be necessary to provide part of the series compensating reactance 7, 8 in the form of separate elements.

For example, a 200 ohm characteristic impedance concentric or coaxial conductor transmission line corresponds to a 28:1 ratio of outer to inner conductor diameters, and since doubling this ratio merely means an increase in characteristic impedance to 242 ohms, 200 ohms may be taken as a reasonable practical upper limit of coaxial line characteristic impedance.

Then if the required bandwidth is $\pm 20\%$ of the mean operating frequency, the reactance compensation for a short-circuited half wave line is $\pm 200 \tan 36^\circ = \pm 145$ ohms. This amount of compensating impedance can thus be obtained for each half wave length of antenna, that is 290 ohms compensation for a balanced antenna, so that if the antenna has 350 ohms peak resistance, the use of a compensating line having the characteristic impedance of 200 ohms leaves only $350 - 2 \times 145 = 60$ ohms for further compensation or neutralisation to be obtained. This may easily be done, for example, by a 150 ohm capacity and inductive reactance in series.

The different elements will be described. The first is a closed stub loaded to be equivalent to a half wave length short circuited stub. This expedient is illustrated in Fig. 9 in which the coupling short length of transmission line 17 is coupled to the lower end of the unbalanced antenna 4, 5, 6 by a capacity 8 and accommodated within the antenna is a closed stub 10 loaded to half wave resonance by a capacity 12 lying in a matching zone within one quarter wave length (mean operating frequency) from either end of

the stub and connected between the two concentric conductors of the stub. This capacity 12 is adjusted by means represented at 13 so as to bring the lower portion of the stub into quarter wave resonance at the mean operating frequency by series tuning and at the same time parallel tuning the upper closed stub and this combination makes the impedance across the open or lower end of the stub, when it is connected to the antenna, zero at the mean operating frequency. It will be realised that the stub is effectively in series between the antenna and line 17 and gives a good degree of reactance compensation between the antenna and the reactances as seen through the portion of transmission line 17. The characteristic impedance of the stub 10 is chosen, for example by suitable diameter of central conductor 11 so that the reactance seen across its lower end is substantially equal and opposite to twice the reactance at the base of the antenna, at frequencies near the outer limits of the operating frequency band, that is at these frequencies, the reactance of stub 10 is equal to the sum of the reactance of the antenna at the base thereof and the combined reactances at the base of the antenna of the parallel tuned circuit 1, 2 and of the length of transmission line 17 and condenser 8.

The location of the condenser 12 may be used to make the reactance characteristic across the lower end of the stub vary unsymmetrically with frequency about the mean operating frequency to an extent that matches the unsymmetrical reactance characteristic of the antenna with respect to the mean operating frequency.

Whilst Fig. 9 is shown as an unbalanced antenna connected to one side of the transmission line 17, the other side of which would normally be earthed, it will be understood that another dipole element similar to that shown may be connected to the other side of line 17, instead of earth potential, forming a balanced system.

The other expedient which enables antennae of higher characteristic impedance and radiation resistance to be used is illustrated in Figs. 10, 11 and 12 and consists in adding the series reactance of a parallel undamped circuit at the end of a quarter wavelength of line resonant at substantially the mean operating frequency in series with the antenna.

Fig. 10 shows diagrammatically the quarter wave line 14 open at the end A which is connected at the base of the antenna, and loaded at its other end with the parallel tuned circuit 15 represented by capacity 16 and loop 17, and resonant at the mean operating frequency. In effect the impedance of circuit 15 is thus in series with the antenna because the parallel tuned circuit when seen through the quarter wave line 14 resonant at the mean operating frequency has substantially the same reactance neutralisation effect or compensation as a series tuned circuit at the open end A (Fig. 10).

Let the parallel impedance of the circuit 15 at the end of the transmission line 14, Fig. 10, of impedance Z_0 be jX , then the input reactance is given by

$$Z_{\text{input}} = jZ_0 \tan \left[\frac{2\pi l}{\lambda} + \tan^{-1} \frac{X}{Z_0} \right]$$

where X is negative for frequencies above resonance where

$$\frac{2\pi l}{\lambda} > 90^\circ$$

is physical length of the line 14.

Since X is the impedance of a parallel tuned circuit this may be rewritten.

$$= jZ_0 \tan \left[\frac{2\pi l}{\lambda} + \tan^{-1} \frac{\omega_1 L}{Z_0 \left[1 - \left(\frac{\omega_1}{\omega_0} \right)^2 \right]} \right]$$

where

$$\omega_1 = 2\pi \times \text{frequency } f_1$$

$$\omega_0 = 2\pi \times \text{mean operating frequency.}$$

Examination of this expression shows that the best reactance compensation occurs when the ratio of the correcting reactance at the input terminals 20 to the characteristic impedance of the

$$\frac{\lambda}{4} \text{ line } (Z_0)$$

is not large compared to 1.

However, taking for example $f_1 = 0.8 f_0$ and $f_2 = 0.9 f_0$ we have as follows:

f_1 Z input	f_2 Z input	Ratio Z_{f2}/Z_{f1}
4.0 jZ_0	1.02 jZ_0	2525
3.0 jZ_0	0.892 jZ_0	0.290
2.0 jZ_0	0.687 jZ_0	0.344
1.5 jZ_0	0.560 jZ_0	0.373

showing that although the ratio of the reactance near resonance to that giving perfect compensation at the peaks of the reactance characteristic is low compared to the ideal to give perfect compensation for a reactance characteristic convex outwards on both sides of the line of zero resistance reasonable compensation can be obtained with neutralising reactances up to three times the characteristic impedance of the line for band widths of the order of $\pm 20\%$ of the carrier frequency.

It may be noted that although two quarter wavelength transmission lines in series may be used as an impedance reducing mechanism, they generally result in considerable reduction of the band width, but the principles of the invention may be applied to the antenna as seen through two quarter wavelengths transmission lines in series.

Two embodiments utilising the expedient as described in relation to Fig. 10 are illustrated in Figs. 11 and 12. In these figures the transmission line 14 takes the form of a quarter wave concentric line 14' and the parallel tuned circuit comprises a portion of transmission line less than one quarter wave length long at the mean operating frequency closed at its outer end 18 and tuned into resonance by the variable capacity 19 connected between the two coaxial conductors at the end of the quarter wave length 14'. The portion 14' is connected directly to the base of the antenna 4, 5, 6 and the parallel tuned circuit 1, 2 is connected to the central conductor of the stub at the base of the antenna. From what has already been stated it will be clear that the line arrangement 14', 18, 19 has the effect of a series tuned circuit and this connects the parallel tuned circuit 1, 2 to the antenna 4, 5, 6.

Fig. 11 shows a balanced antenna and an unbalanced transmission line whose coaxial conductors are tapped at appropriate points on the in-

ductance represented as loop 1. In Fig. 12 is shown an unbalanced antenna and an unbalanced transmission line 3, the parallel circuit 1, 2 taking the form of a section of coaxial transmission line closed at one end and tuned to resonance at the mean frequency by a capacity 2 connected across the conductors at the other end to which the transmission line is connected, the tapping point of the inner conductor of 3 being suitably chosen on the inner conductor of 1.

While several embodiments of the invention have been described and illustrated, others falling within the scope of the invention as defined in the appended claims will occur to those skilled in the art. For example, cylindrical antenna with conical ends may be used, the overall characteristic impedance of the cylindrical portion being properly matched to the characteristic impedance of the conical portion at their junctions. Furthermore, balanced or unbalanced antennae may be used with balanced or unbalanced transmission lines.

References in the claims to a series-tuned circuit are intended in appropriate instances to include a portion of transmission line operating as such a circuit.

What is claimed is:

1. A system for coupling an antenna to an input transmission line so as to have a low degree of overall mismatch between the impedances throughout a broad band of ultra high frequencies comprising a coupling transmission line, an antenna including a pair of end-fed radiating elements half wave resonant substantially at the mean operating frequency of the band, a series tuned circuit resonant substantially at said mean frequency coupled to said antenna, a parallel tuned circuit resonant substantially at said mean frequency coupled to said series tuned circuit and said coupling transmission line and having substantially the same "Q" as the antenna, the reactances of said series tuned circuit being dimensioned to neutralize the reactances of both said parallel tuned circuit and said antenna off resonance, said antenna comprising a pair of hollow elements and said series circuit comprising a quarter wave stub resonant substantially at the mean operating frequency accommodated within each hollow antenna element and connected to said antenna element at one

end thereof and a second parallel tuned circuit resonant substantially at the mean operating frequency and connected to said stub at its other end.

2. A system as claimed in claim 1 wherein said second parallel tuned circuit is incorporated in a half wave closed stub, provided with a capacity at an intermediate point and connected between the concentric conductors of the stub, arranged to tune the portion including the open end into resonance at substantially the mean operating frequency and to parallel tune the other portion including the closed end into resonance substantially at the mean operating frequency, and the said parallel tuned circuit formed with the transmission line is connected directly to said stub at its point of connection to the antenna.

3. A system according to claim 2 in which the said parallel tuned circuit comprises a wire loop connected on either side to the central conductor of the stubs and a capacity connected between said central conductors of said stubs.

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