June 10, 1969 K. G. SCHROEDER 3,449,751

COMPLEMENTARY PAIR ANTENNA ELEMENT GROUPS

Filed Sept. 20, 1965 Sheet 1 of 10

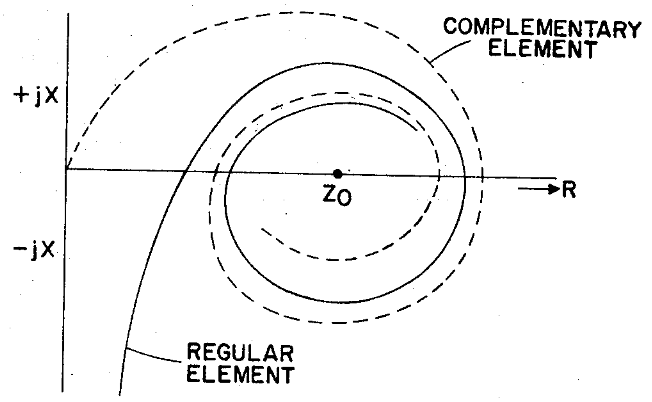

FIG 16

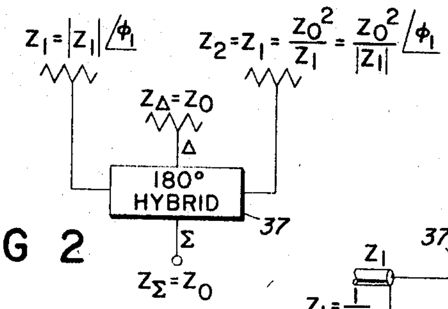

FIG 2

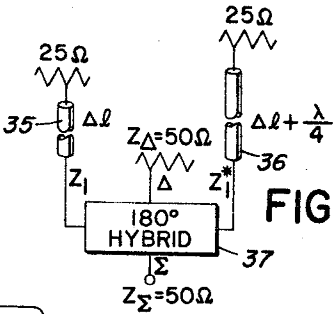

FIG 4

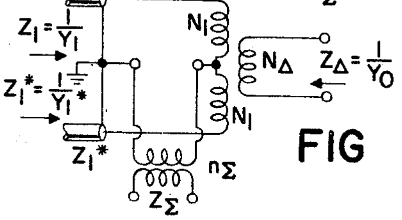

FIG 1

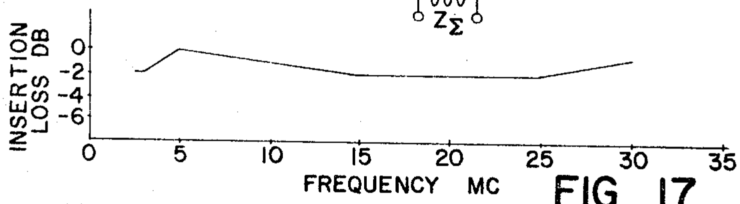

FIG 17

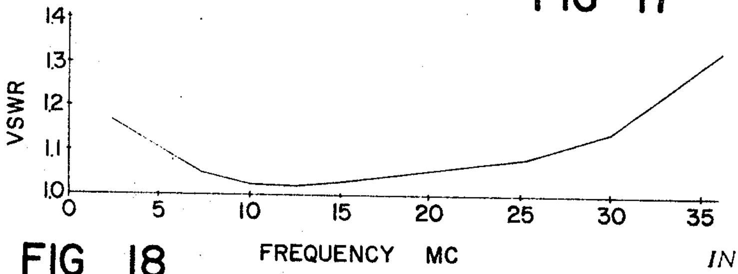

FIG 18

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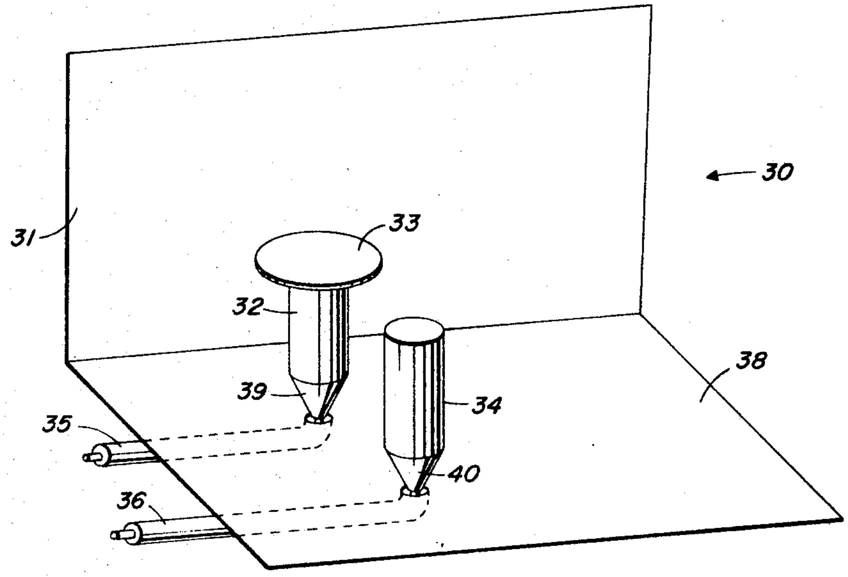

FIG 3

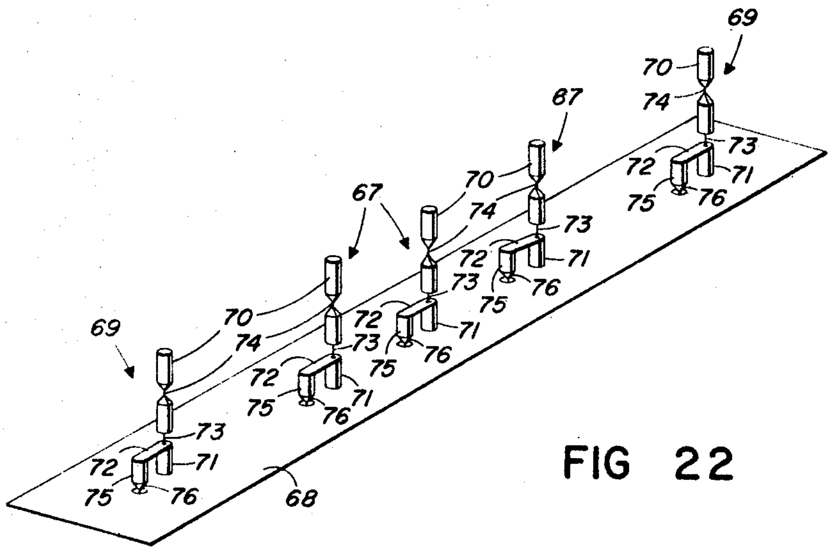

FIG 22

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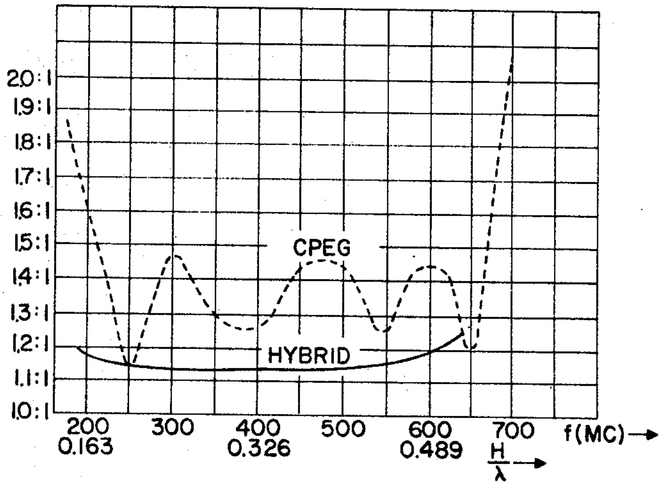

FIG 5

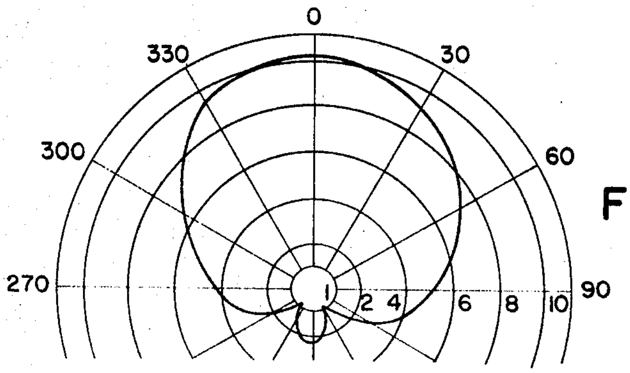

FIG 7

F=180 MC

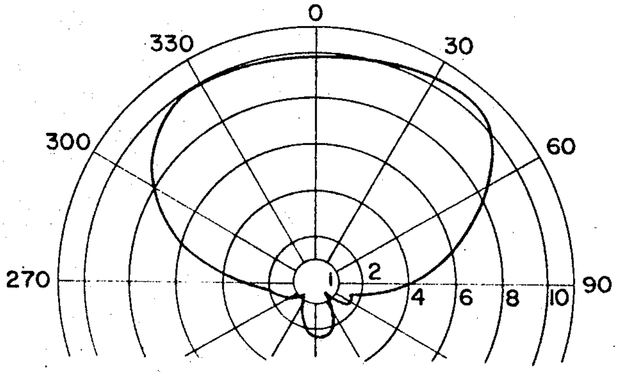

FIG 8

F=400 MC

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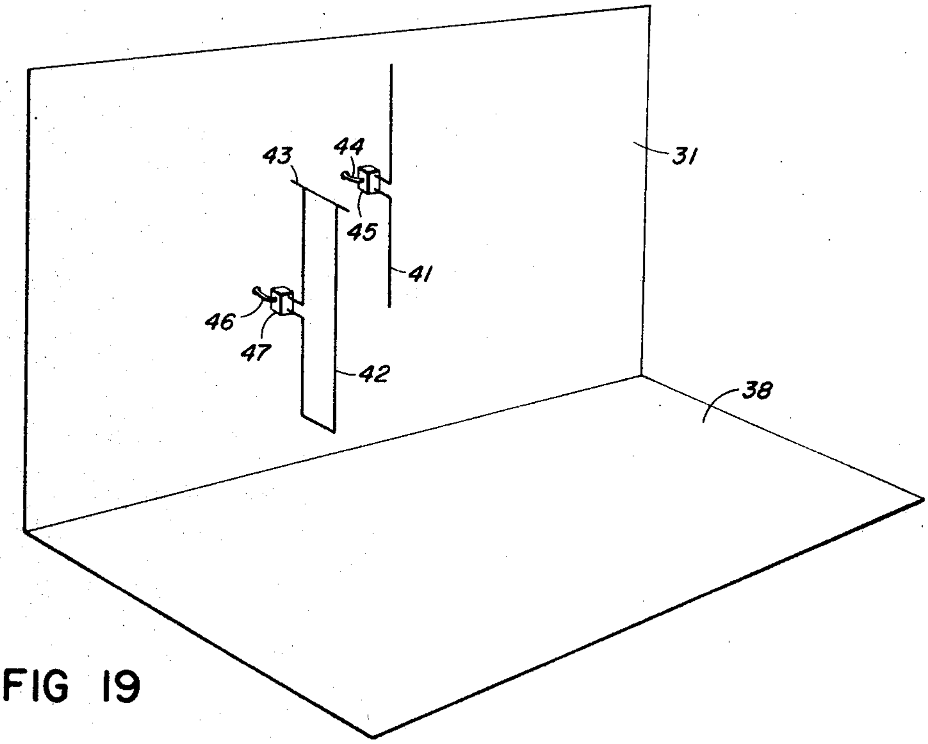

FIG 19

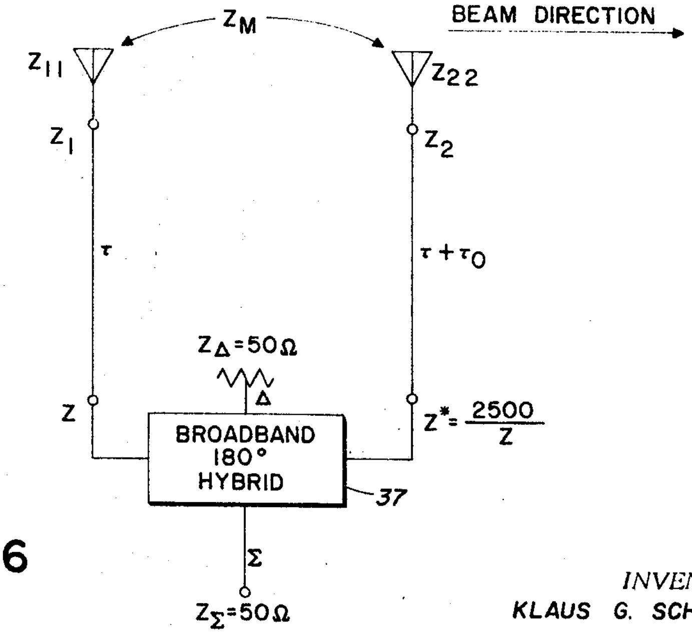

FIG 6

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June 10, 1969 K. G. SCHROEDER **3,449,751**

COMPLEMENTARY PAIR ANTENNA ELEMENT GROUPS

Filed Sept. 20, 1965 Sheet 5 of 10

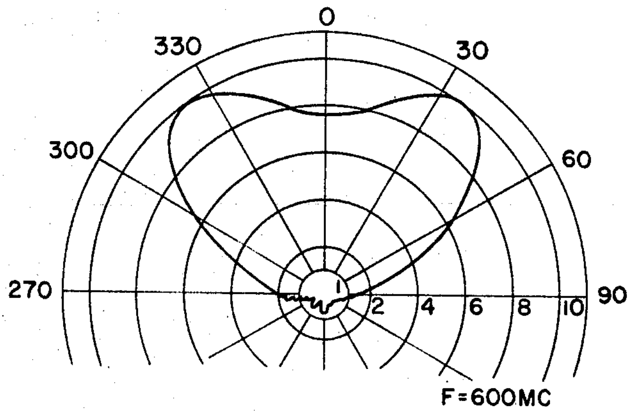

FIG 9

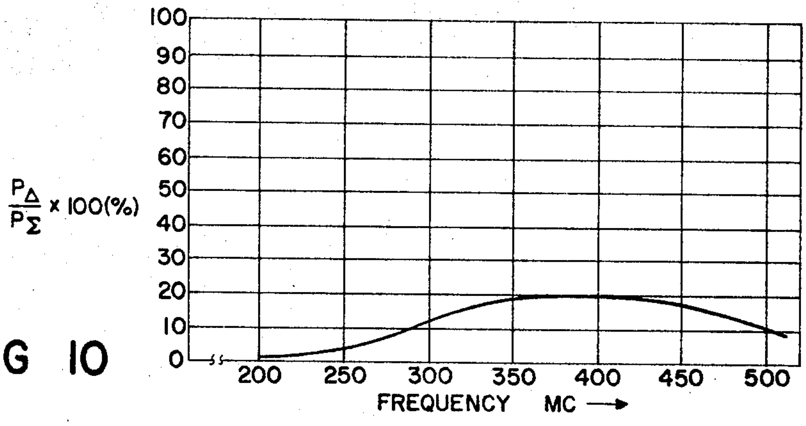

FIG 10

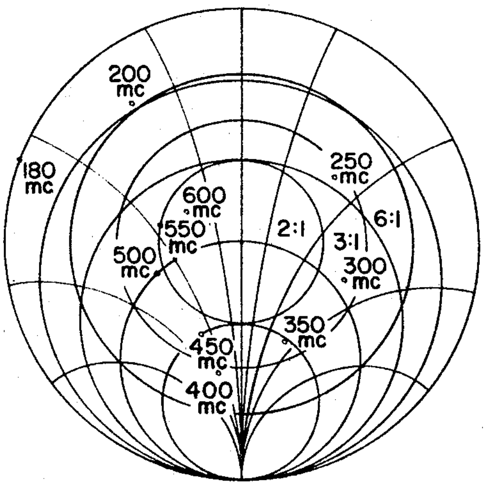

FIG 11

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FIG 12

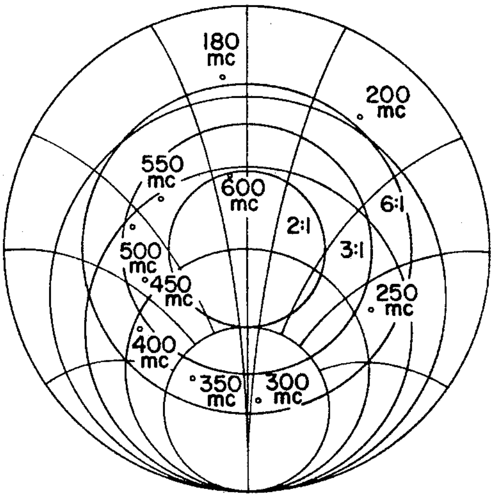
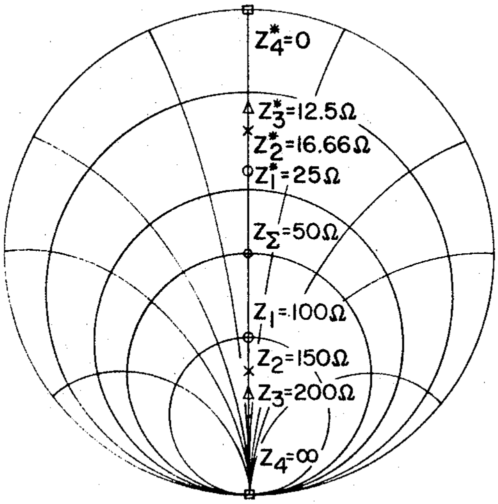


FIG 13



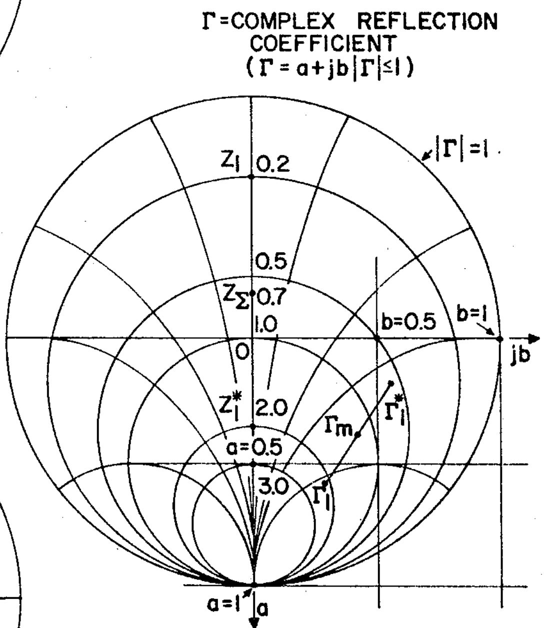


FIG 15

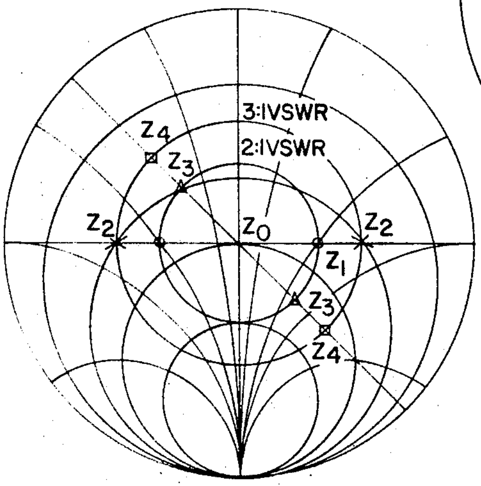


FIG 14

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June 10, 1969 K. G. SCHROEDER **3,449,751**

COMPLEMENTARY PAIR ANTENNA ELEMENT GROUPS

Filed Sept. 20, 1965 Sheet 7 of 10

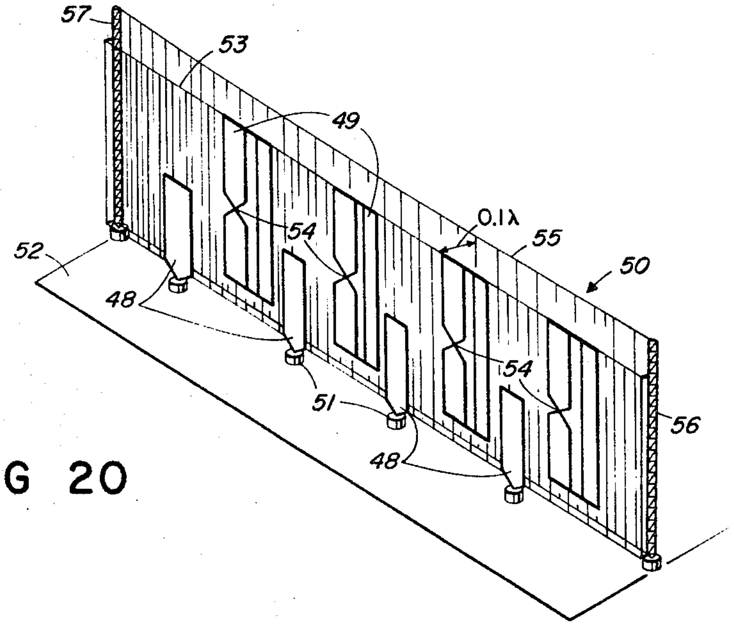

FIG 20

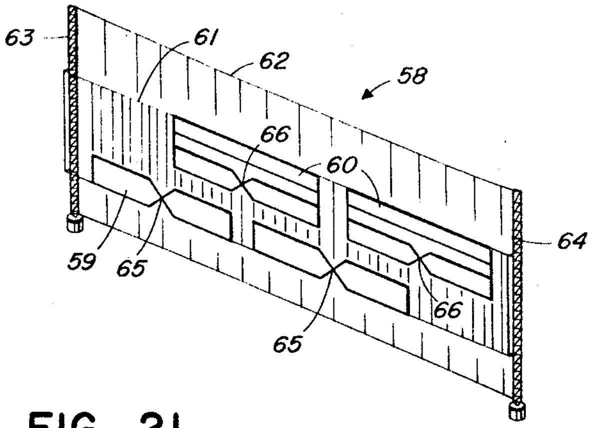

FIG 21

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June 10, 1969 K. G. SCHROEDER **3,449,751**

COMPLEMENTARY PAIR ANTENNA ELEMENT GROUPS

Filed Sept. 20, 1965 Sheet 8 of 10

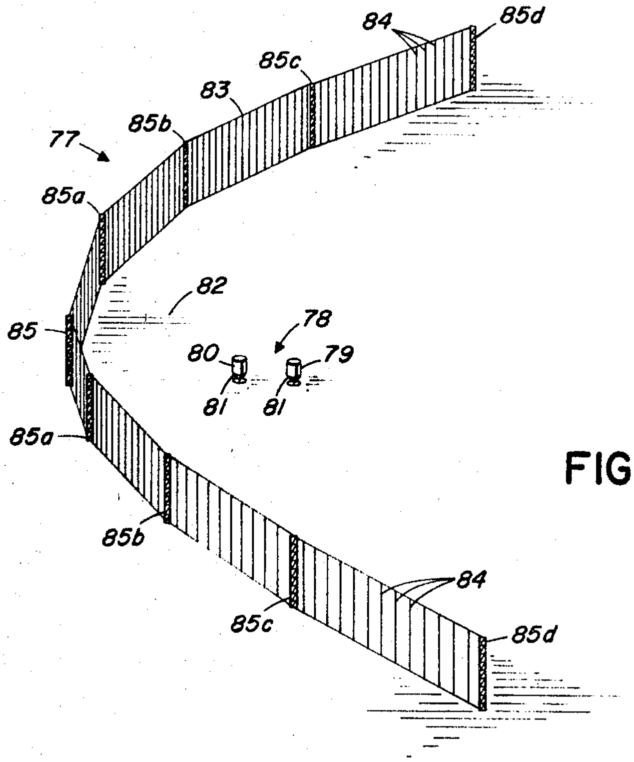

FIG 23

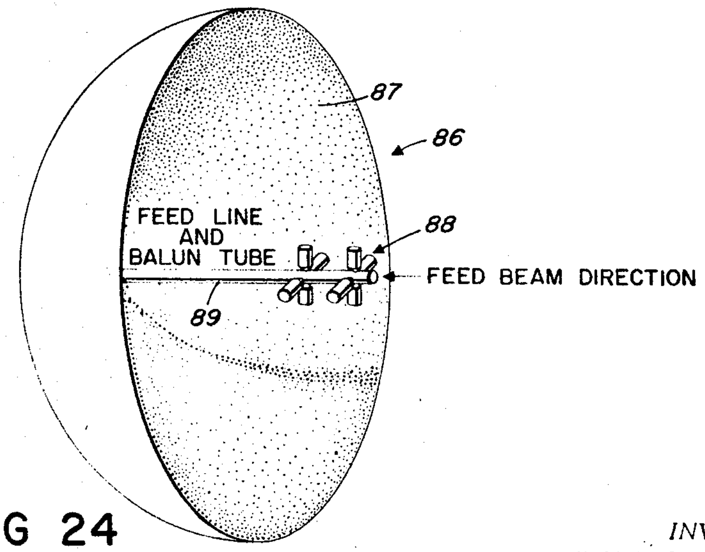

FIG 24

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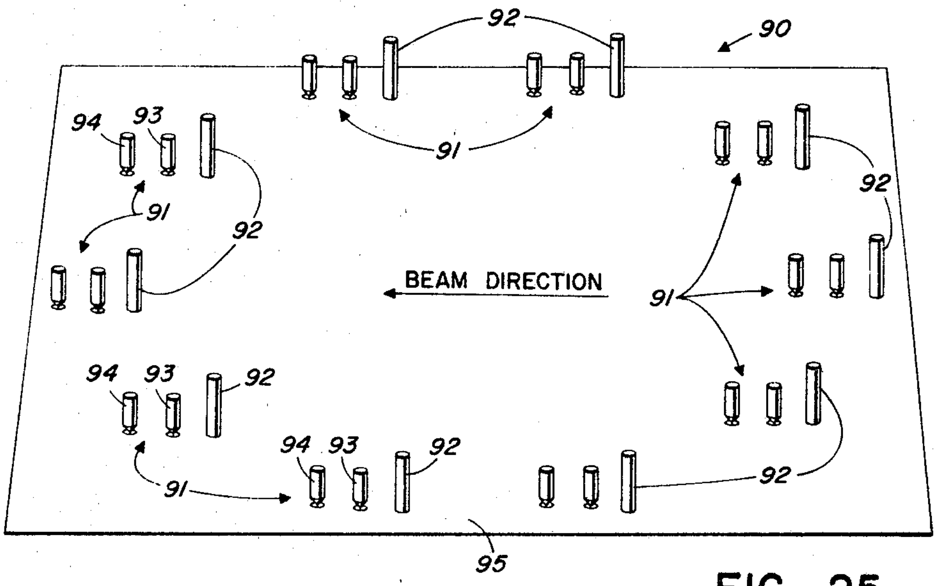

FIG 25

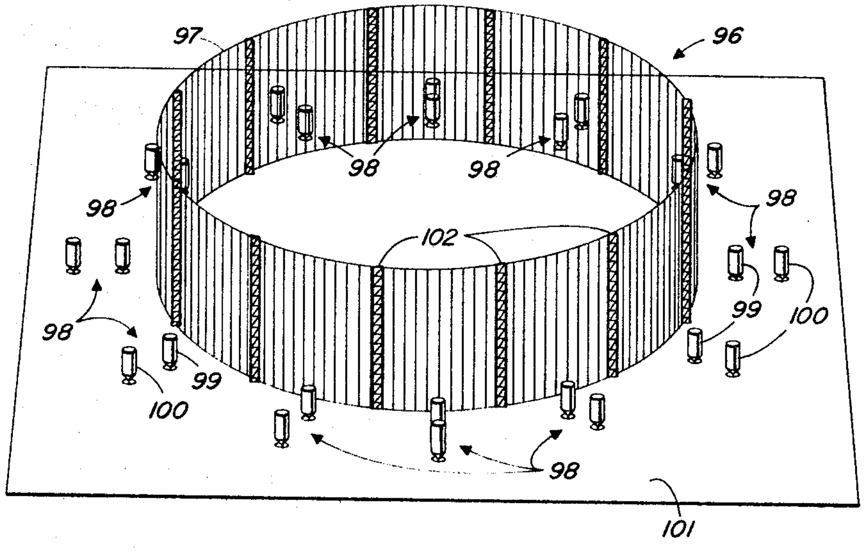

FIG 26

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June 10, 1969 K. G. SCHROEDER **3,449,751**

COMPLEMENTARY PAIR ANTENNA ELEMENT GROUPS

Filed Sept. 20, 1965 Sheet 10 of 10

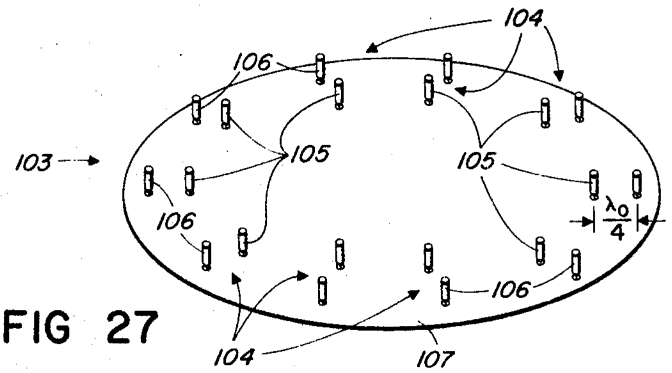

FIG 27

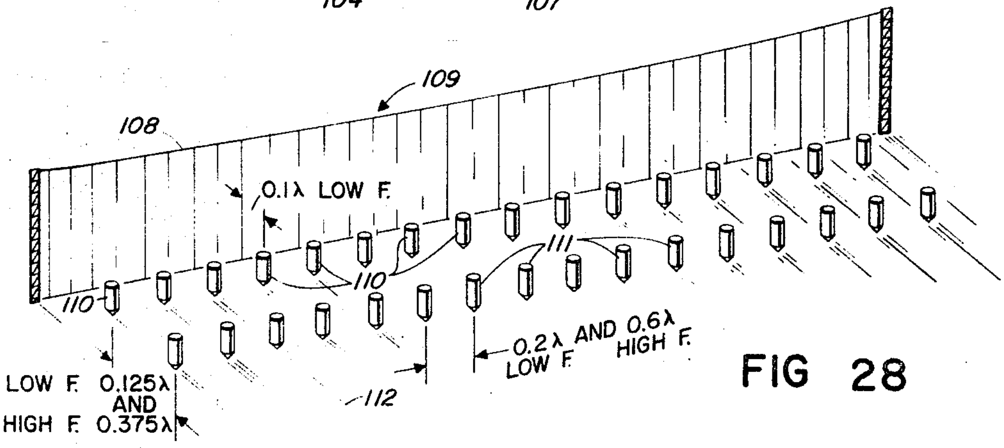

FIG 28

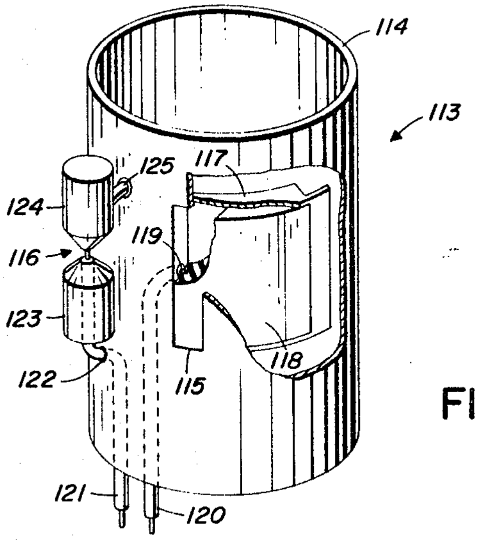

FIG 29

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United States Patent Office 3,449,751
Patented June 10, 1969

3,449,751

COMPLEMENTARY PAIR ANTENNA ELEMENT GROUPS

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Filed Sept. 20, 1965, Ser. No. 488,541
Int. Cl. H01q *21/00, 1/50, 19/12*
U.S. Cl. 343—727 20 Claims

ABSTRACT OF THE DISCLOSURE

A new class of broadband antennas with automatic impedance matching through combining two elements as a complementary pair in such a way that the reflection coefficients cancel. This is accomplished by using two antenna elements with complementary imepance characteristics and feeding them with a 180 degree hybrid so that the radiation produced by the two elements is additive in the desired propagation direction.

This invention relates in general to various antenna systems with broadband operational capabilities, and in particular to antenna systems utilizing complementary paired element groups with each pair fed by a 180 degree hybrid and with each element of respective pairs of elements radiation mutually coupled to a relatively high degree.

With large, in terms of wavelength, unidirectional antenna arrays in the HF, VHF and UHF frenquency ranges where more than approximately an octave of bandwidth is required, the untuned element VSWR (voltage standing wave ratio) in front of a reflector is usually around 2:1. This results, with many existing antenna systems, in problems with large amounts of reflected power disturbing, for example, phasing circuit mechanisms (particularly under beam steering conditions) which can also overload a transmitter. With applicant's complementary pair element groups reflected energy is channeled into assigned terminations providing a well matched impedance for circuit element pairs excitable as effectively one element in a high gain broadside array. Such structure provides for ultimate limitation in operational bandwidth as determined by the element pattern and with a desired expansion approximately to the 4:1 frequency range.

A new class of broadband antennas is provided which automatic impedance matching is achieved by combining two elements in such a way that the reflection coefficients cancel. Applicant has accomplished this by selecting two antenna elements with complementary impedance characteristics and feeding them with a 180 degree hybrid so that the radiation produced by these two elements is additive in the desired direction and with such a pair of elements called a complementary pair element group. Various antenna system complementary pair element groups providing such operation in appropriately designed relation are a vertical dipole and a folded dipole complementary pair, and an endfire monopole complementary pair structure, a structure that is a near optimum radiator for vertically polarized steerable antenna arrays, such as super power high frequency transmitting arrays. Such complementary pair element groups are quite useful in many other antenna systems including, for example, the linear and circularly polarized feeds, paraboloids and paracylinders, endfire element groups in vertically polarized circular antenna systems, and stacked element groups in endfire arrays with non-uniform element spacing. Among excellent operational applications are communications, high-quality broadcasting, air traffic control, radar, track, spectrum surveillance and radio astronomy. It should be realized that these groups are very useful both in antenna transmitting systems and receiving systems and provide a more economical, highly efficient and much more flexible antenna operational installation than heretofore provided by other existing antenna radiating and receiving systems.

It is, therefore, a principal object of this invention to provide improved antenna systems with a desired radiation pattern and broadband impedance matching with both substantially independent of installation environmental variances.

Another object is to provide complementary pair element group antenna structures with greatly expanded broadband full range adaptable impedance matching.

A further object is to provide such transmitting and receiving antennas having almost unlimited gain.

Features of this invention useful in accomplishing the above objects include in the various embodiments a 180 degree hybrid feeding the two elements of each pair of elements forming a complementary pair element group in each antenna system. The two elements of each complementary pair have input impedances that are substantially complementary, that is, with the impedance of one being Z_0/VSWR and the other being Z_0 times VSWR with Z_0 being the characteristic impedance of each respective element as resistances into the respective elements. This results in the impedances being located 180 degrees apart or substantially so on the same VSWR circle of a Smith Chart (such as referred to hereinafter). The two elements of each complementary pair are so spaced, positioned and designed as to have a relatively high degree of radiation mutual coupling. There are basically two different types of complementary pairs that may be employed in applicant's improved antenna systems including, first, those which are truly complementary in the Babinet sense, such as a slot and dipole, and also those which can be designed to be complementary, such as dipoles and folded dipoles; and secondly, those which are externally complementarized by special circuit techniques.

Specific embodiments representing what is presently regarded as the best mode of carrying out the invention are illustrated in the accompanying drawings.

In the drawings:

FIGURE 1 represents the schematic circuit diagram of a 180 degree hybrid circuit such as used in feeding the various complementary pair element group equipped embodiments;

FIGURE 2, a combination block and schematic illustration of the general impedance relations involved in use of 180 degree hybrids;

FIGURE 3, a perspective view of an endfire complementary pair element group mounted above and fed through a ground plane and equipped with a reflector;

FIGURE 4, a showing of a 180 degree hybrid feeding two 25-ohm terminating effective resistances or characteristic impedances of two of the elements of an element group with the elements made to appear complementary through the use of two coaxial lines with one a quarter of a wavelength of the operational bandwidth center frequency longer than the other;

FIGURE 5, a graph of voltage standing wave ratio (VSWR), of an end-fire monopole complementary pair element group with reflector as shown in FIGURE 3 through the operational bandwidth range;

FIGURE 6, a schematic showing of a broadband endfire complementary pair feed circuit;

FIGURES 7, 8 and 9, H-plane pattern graphs at frequencies of 180 mc., 400 mc., and 600 mc., respectively, of an endfire monopole complementary pair element group embodiment with back lobe limitation determined by the reflector size;

FIGURE 10, a percentage power absorbed by difference port load for an endfire monopole complementary pair element group through the frequency range of operation graph;

FIGURE 11, a Smith Chart showing optimized locus of an endfire monopole complementary pair element group front element having an impedance Z_0 equal to 50 ohms;

FIGURE 12, the corresponding plot for the back element through the same frequency range;

FIGURE 13, a plot of resistive loads on a Smith Chart with respect to zero reactant complementary loads;

FIGURE 14, a showing of arbitrary complementary loads with approximately 2:1 and 3:1 standing wave ratios;

FIGURE 15, a Smith Chart overlay on the complex reflection coefficient plane;

FIGURE 16, a plot of the beam impedance characteristics of dipoles and folded dipoles;

FIGURE 17, a plot of measured insertion losses for a high power, high frequency 180 degree hybrid through an extended operational frequency bandwidth range;

FIGURE 18, a graph of measured sum port VSWR with a high power, high frequency 180 degree hybrid through a corresponding frequency range;

FIGURE 19, a perspective view of a vertical dipole and folded dipole complementary pair element group mounted on a reflector and with a ground plane;

FIGURE 20, a broadside reflector antenna array with vertical monopole and folded dipole complementary pair element groups;

FIGURE 21, a broadside reflector array with horizontal dipole and folded dipole complementary pair element groups;

FIGURE 22, a non-uniformly spaced endfire antenna array of vertically stacked folded monopole and dipole complementary pair element groups;

FIGURE 23, a vertical paracylinder antenna with endfire monopole complementary pair element group feed;

FIGURE 24, a paraboloidal reflector antenna using a cross polarized endfire dipole complementary pair element group feed;

FIGURE 25, a fixed bearing circular antenna array of endfire monopole complementary pair element groups with individual element group post-type reflectors;

FIGURE 26, an endfire monopole complementary pair element group equipped Wullenweber antenna;

FIGURE 27, a circular antenna array of endfire monopole complementary pair element groups;

FIGURE 28, a perspective view of a 32-element monopole antenna array with the elements arranged in 16 endfire complementary pair element groups and with a reflector; and,

FIGURE 29, a perspective view of a self-supporting, cylinder miniature slot and dipole complementary pair element group antenna for circularly-polarized UHF transmission.

Referring to the drawings:

With the new complementary pair element groups a broadband impedance match is accomplished by feeding two antenna elements with complementary characteristics from one hybrid junction. This new useful system is embodied in many various antenna environmental embodiments such as element groups including a vertical dipole and folded dipole, and the endfire monopole complementary pair which is a near-optimum radiator for vertically polarized steerable arrays such as super power HF transmitting arrays. These two embodiments are described in detail hereinafter along with various other embodiments to lesser or the same extent. Such embodiments advantageously provide for very broadband operation of high gain broadside reflector antenna arrays and is also extremely useful in a considerable variety of other antenna systems. Examples are linearly and circularly polarized feeds for paraboloids and paracylinders, endfire element groups in vertically polarized circular arrays, and stacked element groups in endfire arrays with non-uniform element spacing.

Elements in naturally complementary pairs in an antenna system have to be arrayed side by side in back element and forward element planes perpendicular to the desired beam direction to provide broadside complementary pair element groups. The following table is a partial summary of complementary element pairs either naturally complementary or with the potential of being so designed and arranged as to be substantially complementary.

TABLE 1

(1) Dipole—Slot
(2) Vertical dipole—Folded vertical dipole
(3) Horizontal dipole—Folded horizontal dipole
(4) Vertical monopole—Folded vertical dipole
(5) Vertical monopole—Folded horizontal dipole
(6) Vertical dipole—Folded vertical monopole
(7) Vertical dipole—Folded horizontal dipole
(8) Horizontal dipole—Folded vertical monopole
(9) Slot—Folded slot
(10) Folded dipole—Folded slot
(11) Dipole—Orthogonal dipole
(12) Folded dipole—Orthogonal folded dipole
(13) Slot—Parallel folded dipole
(14) Folded slot—Parallel dipole

The impedance characteristics of the elements within each pair do not necessarily rotate about the same point on a Smith Chart and only the vertical monopole locus can be made to rotate around 50 ohms. However, the center points of the impedance characteristics can be transformed to 50 ohms, or any other characteristic impedance. As an example, a narrow slot and thin dipole are complementary with respect to half the intrinsic impedance of free space, or approximately 60π ohms. A complementary pair element group of these elements has to be fed by a hybrid having a characteristic impedance of substantially 60π ohms. Since this is difficult to achieve, a practical approach is to get down to a 50 ohm line impedance by means of a step-down transformer with approximately a 4:1 transformation ratio. A crucial part of the various complementary pair element group embodiments is a 180 degree hybrid, such as shown in FIGURE 1, various embodiments of which are fairly well known. Such a hybrid, also known to microwave people as the "Magic T," has the property that any signal applied to the summation terminals of sum port Z_Σ is distributed into two phase components at the terminal pairs Z_1 and Z_1^*. A signal applied to the Z_Δ pair of terminals results in two components for Z_1 and Z_1^* which, while they are of equal amplitude, are 180 degrees out of phase. An important property of such hybrids is their ability to average reflection coefficients. From the emittance matrix of this structure, the sum port Z_Σ emittance is usually converted in a conventional way into the sum port impedance.

$$Z_\Sigma=\frac{n_\Sigma^2\left(\frac{N_1^2}{Z_1}+\frac{N_1^{*2}}{Z_1^*}+\frac{N_\Delta}{Z_\Delta}\right)^2}{(N_1+N_1^*)^2\frac{1}{Z_1Z_1^*}+\frac{N_\Delta^2}{Z_\Delta}\,\frac{1}{Z_1}+\frac{1}{Z_1^*}}$$

Equation (1)

Letting $N_1=N_1^*=1$ and $N_\Delta=n_\Sigma=\sqrt{2}$ the sum port impedance simplifies to

$$Z_\Sigma=\frac{\frac{1}{Z_1}+\frac{1}{Z_1^*}+\frac{1}{Z_\Delta}}{\frac{2}{Z_1Z_1^*}+\frac{1}{Z_\Delta}\left(\frac{1}{Z_1}+\frac{1}{Z_1^*}\right)}$$

Equation (2)

If the difference port is terminated, and the output impedances are complementary with respect to the characteristic impedances of the hybrid, i.e.,

$$Z=Z_0$$

and

$$Z_1^*=Z_0^2/Z_1$$

then the sum port impedance is finally:

$$Z_\Sigma=\frac{\frac{Z_1+Z_1^*}{Z_0^2}+\frac{2}{Z_0}}{\frac{2}{Z_0^2}+\frac{1}{Z_0}\,\frac{Z_1+Z_1^*}{Z_0^2}}=Z_0$$

Equation (3)

These impedance relationships are illustrated in FIGURE 2 with a load impedance Z_1 at one output port and Z_0^2/Z_1 at the other output port and with the sum port Z_Σ impedance equal to Z_0.

The useful frequency range of complementary pair element groups in an antenna environment is limited by the E-plane pattern of the individual elements to approximately 4:1, but this is about the maximum bandwidth of broadside phased arrays. This is because beam steering to say as much as to an angle ϕ of 40 degrees requires that element spacing be less than 0.6λ (wavelength) if grating lobes are to be avoided. Since spacing S between the elements has to be substantially

$$S<\frac{\lambda}{1+[\sin \phi]}$$

For a 4:1 frequency range, the spacing between elements of a complementary pair is then approximately 0.15 wavelength at the lowest frequency, a spacing that should be the minimum tolerable spacing with respect to mutual coupling variation. The fact that colinear complementary pair elements cannot be spaced that closely leads naturally to the selection of parallel radiators. Vertical monopoles above a conducting ground plane are very economical because they do not require balancing networks. They can be fed directly from a coaxial feed system, and further, they have resistances below 50 ohms in the vicinity of first resonance. Thus, no additional transformation is necessary to get the center of the monopole impedance locus approximately at 50 ohms.

An endfire pair broadband monopole embodiment **30** of FIGURE 3 reflector **31** assures high front-to-back ratio at all frequencies but it should be noted that this endfire complementary pair element group can be designed in an antenna system without the reflector. The rear element **32** has a top loading extended planar end **33** for fine adjustment of the sum port Z_Σ impedance of the total complementary pair element group circuit network. The impedance locus of the rear element **32** shows a larger VSWR than the front element **34** since the back element is closer to the reflector **31**. These optimized elements are now complementarized as is shown in FIGURE 4, assuming that both element impedances are approximately 25 ohms with the rear element **32** and the forward element **34** being fed through coaxial lines **35** and **36** respectively from a 180 degree hybrid **37**. The connections coaxial lines **35** and **36** are with outer sheaths to ground plane **38** and the inner conductors directly to the bottom conical apexes of the feed ends **39** and **40** of the rear element **32** and forward element **34**, respectively. With both the rear and forward impedances approximately 25 ohms one of the monopoles can be made to be complementary by feeding it through a coaxial transmission line which is a quarter of a wavelength longer at midband of the frequency range than the length of the line feeding the other element. This is accomplished by making line **36** a quarter of a wavelength longer than the coaxial line **35** in the embodiment **30** of FIGURE 3. Then the 180 degree hybrid **37** automatically matches these two impedances together, because the conditions required for the formula $Z_1^*=Z_0^2/Z_1$ are satisfied. Even though this condition is exactly true only at the center frequency, a 3:1 bandwidth is easily realized, i.e., the complementarization is effective for a feed line differential length from

$$\frac{\lambda}{8}\text{ to }3\frac{\lambda}{8}$$

The sum port VSWR of the total endfire monopole complementary pair element group with reflector is shown in FIGURE 5. The solid line represents the sum port VSWR for 50 ohm coaxial terminations at the two output ports. Normally is should not be possible to get a better match than this hybrid VSWR, but due to apparent reactance compensation at 650 mc. (which was beyond the hybrid design band) a slightly better VSWR resulted for the complementary pair element group. It is interesting to note that "equal-ripple" characteristic of the input standing wave ratio, which is due to the various factors contributing to the over-all complementary pair element group performance. At 400 mc., the center frequency of the design band, the standing wave ratio has the expected minimum, because the feed line differential is exactly λ/4, and rotates one impedance into a complementary position with respect to the other. At lower frequencies lower minimum VSWR's can be expected, corresponding to the larger bandwidth and better match of the hybrids. FIGURE 6 shows the total near-field beam forming mechanism, which is applicable to both monopole and dipole endfire complementary pair element groups, even though the self- and mutual impedances are different. For broadband patterns a time delay differential τ_0 is used in the front element feed line, where τ_0 is the wave delay between the front and the back elements.

Representative H-plane patterns are shown in FIGURES 7, 8 and 9, the blacklobe being determined by the limited reflector size. The changes in the H-plane patterns are due to the fact that only at the center frequency f_0 (400 mc.) the time delay τ_0 is equal to $\lambda_0/4$, so that a high front-to-back ratio results in the cardioid pattern. At $0.5f_0$ and $1.5f_0$ (200 and 600 mc.) the time delay differential is equal to

$$\frac{\lambda}{8}\text{ and }3\frac{\lambda}{8}$$

respectively, the backlobe peak is only down about 3 db from the forward beam peak, resulting in a narrower pattern at 200 mc., and a dip in the center at 600 mc., according to the spacing of the phase center from the reflector. The H-plane patterns can be adjusted by moving the group closer to the reflector, without affecting the group impedance match very much. In FIGURE 10 the power absorbed by the difference port load of the complementary pair element group hybrid is shown as a function of frequency. A maximum matching loss of ~20% occurs as expected at the center frequency, because here the self-impedances are maximally complementary, and the mutual impedance (called Z_m in FIGURE 6) is already smal enough to have little effect on the sum port impedance. At 200 mc., however, very little energy is lost in the difference port. Nevertheless, a good impedance match results at 200 mc. of about 1.6:1 VSWR, as compared to the individual monopole mismatches of about 6:1 VSWR. This, mutual impedance Z_m has been successfully employed in the over-all input impedance of the complementary pair element group, with minimum matching loss, and with paired element spacing less than 0.7λ.

The FIGURE 11 shows an optimized locus of an endfire monopole front element having an impedance Z_0 equal to 50 ohms in a complementary pair element group embodiment such as the embodiment **30** of FIGURE 3 in an antenna system designed for an operational bandwidth range approximately 200 to 600 megacycles. The impedance locus for the rear element **32** is given in FIGURE 12 and shows a larger VSWR because the back element is closer to the reflector **31**. Dimensions of a working FIGURE 3 embodiment **30** endfire complementary pair element group antenna system include elements **32** and **34** body diameters of 3 inches, bottom conical apex **39** and **40**, heights of 2.6 inches, rear element **32** spacing of 8.8 inches from the reflector **31**, and forward element **34** spacing an additional 7.5 inches forward from the rear element **32**, and with the element **32** top loading extended planar end **33** being 6 inches in diameter.

Referring again to the hybrids of FIGURES 1, 2, 4 and 6, in complementary pair element group antenna system usage, FIGURE 13 is illustrative of resistive loads on a Smith Chart with respect to zero-reactance complementary loads. Load Z_1 is equal to 100 ohms and its complement Z_1^* is 25 ohms. Together, if terminating a 180 degree hybrid, they result in a matched sum port, even though both have a 2:1 VSWR with respect to 50 ohms. Also, Z_2 and Z_2^*, Z_3 and Z_3^*, and finally Z_4 and Z_4^* (an open circuit and a short) result in a matched sum port. In the last example, all the power sent into the sum port gets absorbed in the difference port, because the totally reflected output signals are 180 degrees out of phase. Those examples were all on the real axis. The next example, in FIGURE 14, shows arbitrary complementary loads, with 2:1 and 3:1 standing wave ratios. It can be readily shown that for any pair of output impedances, even if not complementary, the sum port impedance is always the center of a straight line connecting the two impedances on a Smith Chart.

The 180 degree hybrid of FIGURE 1, known in microwave theory as the "Magic T," operates in a well-known fashion such that any signal applied to the sum port Z_Σ terminals divides into two in-phase components of equal amplitude at the respective Z_1 and Z_1^* terminals whereas a signal applied to the Z_Δ terminals results in two components at the Z_1 and Z_1^* terminals of equal amplitude but 180 degrees out of phase. A less publicized performance characteristic of such 180 degree hybrids is that the reflection coefficient Γ_Σ at the sum port Z_Σ, is equal to the arithmetic mean of the reflection coefficients, Γ_1 and Γ_1^* at the Z_1 and Z_1^* terminals, respectively (i.e.,

$$\Gamma_\Sigma=\frac{\Gamma_1+\Gamma_1^*}{2}\Big)$$

Hence, the sum port impedance Z_Σ, appears on the center of a straight line connecting the two output impedances, Z_1 and Z_1^* on a Smith Chart. Therefore, if Z_1 and Z_1^* are complementary with respect to the system characteristic impedance, Z_0, (i.e., $Z_1=Z_0^2/Z_1^*$) then Z_Σ is equal to Z_0. Applicant has applied this principle successfully in the development of a matched antenna element group for use in phased arrays. However, it should be noted that a significant improvement in sum port impedance match can also be realized even if the impedances Z_1 and Z_1^* are only partially complementary, a fact easily verified by considering the FIGURE 15 Smith Chart plot. For Z_1 equal to $0.2Z_0$ (VSWR of 5.0:1) and Z_1^* equal to $2Z_0$ (VSWR=2.0:1), the sum port impedance Z is $0.7Z_0$ (VSWR=1.4:1).

One may prove mathematically the validity of the above-described averaging principle by obtaining from circuit considerations the expression for the sum port impedance, Z_Σ in terms of the two output impedances, Z_1 and Z_1^*, and comparing this with the expression for the impedance at the center of a straight line connecting Z_1 and Z_1^* on the Smith Chart as follows:

From the admittance matrix, the sum port admittance Y_Σ, is shown to be;

$$Y_\Sigma=\frac{(N_{\Sigma^1})^2(N_1+N_1^*)^2Y_1Y_1^*+N_\Delta^2(Y_1+Y_1^*)Y_\Delta)}{(N_\Sigma)^2(N_1^2Y_1+N_1^*)^2Y_1^*+N_\Delta^2Y_\Delta)}$$

Equation (1A)

Next, the turn ratios will be selected as follows:

$$N_1=N_1^*=N,\ \frac{N_\Delta}{N}=\frac{N_\Sigma}{N_{\Sigma^1}}=\sqrt{2}$$

Now if the difference port is terminated in the characteristic impedance of the transmission system in which the hybrid is used, (i.e., $Z_\Delta=Z_0$), and Equation 1A is normalized with respect to $Y_0(Y_0=1/Z_0)$, we obtain the equation for the sum port impedance of a "matched" hybrid, i.e.,

$$\frac{1}{y_{\Sigma_m}}=z_{\Sigma_m}=\frac{z_1+z_1^*+2z_1z_1^*}{z_1+z_1^*+2}$$

Equation (2A)

where

$$z_{\Sigma_m}=\frac{z_{\Sigma_m}}{z_0},\ z_1=\frac{z_1}{z_0},\ z_1^*=\frac{z_1^*}{z_0}$$

From Equation 2A, it is seen that the hybrid sum port is perfectly matched to the input transmission line when

$$z_1 \text{ and } z_1^*$$

are complementary, e.g., when

$$z_1=\frac{1}{z_1^*},\ z_{\Sigma_m}=1$$

Finally, we will show that for any arbitrary impedances

$$z_1 \text{ and } z_1^*, z_{\Sigma_m}$$

is the impedance at the geometric center of a straight line connecting the two impedances on the Smith Chart.

FIGURE 15 shows a Smith Chart overlay on the complex reflection coefficient plane. Consider the arbitrary reflection coefficients

$$\Gamma_1 \text{ and } \Gamma_1^*$$

If we define Γ_m as the reflection coefficient at the midpoint of a straight line connecting

$$\Gamma_1 \text{ and } \Gamma_1^*$$

then Γ_m is given by,

$$\Gamma_m=\frac{\Gamma_1+\Gamma_1^*}{2}$$

The normalized impedance at this point is given by

$$z_m=\frac{1+\Gamma_m}{1-\Gamma_m}=\frac{1+\frac{1}{2}(\Gamma_1+\Gamma_1^*)}{1-\frac{1}{2}(\Gamma_1+\Gamma_1^*)}$$

Equation (3A)

If we write

$$\Gamma_1 \text{ and } \Gamma_1^*$$

in terms of

$$z_1 \text{ and } z_1^*$$

respectively and substitute in Equation 3A we obtain,

$$z_m=\frac{1+\frac{1}{2}\left(\frac{z_1-1}{z_1+1}+\frac{z_1^*-1}{z_1^*+1}\right)}{1-\frac{1}{2}\left(\frac{z_1-1}{z_1+1}+\frac{z_1^*-1}{z_1^*+1}\right)}$$

Equation (4A)

Simplification of Equation 4A yields

$$z_m=\frac{z_1+z_1^*+2z_1z_1^*}{z_1+z_1^*+2}$$

Equation (5A)

By comparing Equations 2A and 5A it is seen that $z_{\Sigma\ m}=z_m$. Hence the hybrid sum port impedance does, in fact, fall on the geometric center of the straight line connecting the two output impedances on the Smith Chart.

A 180 degree hybrid such as the hybrid **37** of FIGURE 1 with, for example, a 50 ohm load on one output and an open circuit on the other, gives a 3:1 VSWR result, or in a 150 ohm sum port Z_Σ impedance for a 50 ohm hybrid. In such a case, half of the power sent into the sum port is absorbed by the matched load, and the other half is distributed evenly between the difference port and the sum port, for isolations between output ports of about

20 db or greater. For ideally complementary loads, however, the same amount of power gets absorbed by each load, and all of the reflected power gets channelled into the difference port. We thus have 0.5 db "complementarization loss" for 2:1 load VSWR, 1.25 db for 3:1 VSWR, and so on.

These same power balances apply to the individual elements of an idealized complementary pair when fed by a 180 degree hybrid, and consequently to the total complementary pair element group. Obviously, the elements should be most nearly ideally complementary, i.e., have equal VSWR and be on opposite sides of the Smith Chart at all frequencies of the design band. The general impedance characteristics of such theoretical complementary pairs are depicted in FIGURE 16. The impedance locus of each element rotates around a certain center Z_0 point in the complex impedance plane, which is preferably located on the real axis. The element characteristics are then approximately complementary with respect to this center point. When one element has a high impedance, the other one has a low impedance and vice versa. When such a pair of elements is fed with the same 180 degree hybrid, the sum port will be well matched over a very wide frequency range. Theoretically an infinite bandwidth would result, but in practice two factors limit the useful frequency range: The hybrid bandwidth and the E-plane pattern of the elements. The E-plane pattern, in particular, is only good up to about 0.6 wavelength monopole height, or 1.2 wavelengths dipole length. This is not really a limitation for the complementary pair as an element group in large, broadband phased arrays, particularly when beam steering to wide angles is required. In this case the array factor limits the over-all system bandwidth to about 4:1 frequency range anyway, because beam steering to, say, 40 degrees requires that the element spacing be less than 0.6λ (wavelength) if grating lobes are to be avoided, since the spacing S has to be:

$$S<\frac{\lambda}{1+|\sin \phi|}$$

For a 4:1 frequency range, the spacing between elements is then 0.15 wavelength at the lowest frequency, and this should be the minimum tolerable spacing with respect to mutual coupling variation.

If broadband operation over a 4:1 frequency range is desired, the hybrid feeding the complementary pair has to have the same bandwidth. Such broadband hybrids are now available for a variety of frequency ranges and power levels. Particularly at HF and VHF, hybrids with up to 20:1 bandwidth and power levels up to 100 kw. average have already been built and tested. Using one of these high-power HF hybrids, for instance, a complementary pair element group can be designed giving performance approaching ideally a VSWR of 1.1:1 from, say, 6 to 24 megacycles, without the necessity of tuning the elements. The maximum insertion loss will be determined mostly by the (equal) VSWR of the individual elements because such high-power hybrids have insertion losses of typically less than 0.2 db. Assuming a 2:1 VSWR, which is constant with frequency, so that the element impedances rotate around a 50-ohm Smith Chart center, we get an impedance matching insertion loss of about 0.5 db when one of the elements is, e.g., 25 ohms resistive and the other is 100 ohms resistive. The inequality of power split (in the transmitting case) is zero for this case, and very small for most other frequencies for isolations between the two output ports of 20 db or more. FIGURE 17 shows the measured values of insertion loss for a 20 kw. HF hybrid T, and FIGURE 18 the VSWR at the sum port of such a hybrid, when the other ports are matched or terminated in complementary impedances.

An example of naturally complementary elements are the dipole **41** and folded dipole **42** such as shown in FIGURE 19 mounted on a reflector **31** and above a ground plane **38** substantially the same as the similarly numbered reflector and ground plane in the FIGURE 3 embodiment. At very low frequencies, these elements are complementary, one approaching a short, the other an open circuit. In the resonant region between the first three resonances the two elements can be designed to be complementary at a certain frequency, and will stay fairly complementary over about an octave. Larger bandwidths are hard to achieve because of different rates of rotation on the Smith Chart, unless the VSWR specification at the hybrid sum port is somewhat relaxed. Thin dipoles and folded dipoles with a length-to-diameter ratio of about 75:1 are approximately complementary with respect to 180 ohms, so that a 4:1 impedance transforming balun has to be employed before the two impedances may be combined in a 50 ohm hybrid.

It should be noted that in the broadside vertical dipole and folded dipole embodiment of FIGURE 19 giving a unidirectional group pattern, the elements are staggered vertically to minimize any existing detrimental effects of mutual coupling. An approximate optimum trade-off between overall complementary pair element group height and impedance match is provided when the top element is so positioned that its feed point is approximately the same height as the top of the lower element. Further, the folded dipole **42** is provided with an extended element top **43** for added top loading to provide fine adjustment of its impedance with respect to the dipole **41** to provide optimum complementarity over a 2:1 frequency range. The dipole **41** is provided with a feedline **44** connection through the reflector **31** and dipole balun box **45** which is fastened to reflector **31** by conventional means, and folded dipole **42**, in like manner, is provided with a feedline **46** connection through the reflector **31** and folded dipole balun box **47**, which is also fastened to the reflector **31** by conventional means. While individual element impedances of the FIGURE 19 embodiment have as high as 10:1 VSWR at the low end of the design band, if a sum port VSWR of about 3:1 can be tolerated, the frequency range is increased to over 4:1. The azimuth pattern of this complementary pair element group is that of a closely spaced pair in front of a reflector, and changes little with frequency. The general shape of this pattern resembles that of the endfire complementary pair element group, but is somewhat narrower, so that beam steering is only possible to about ±30 degrees if this group is used in an electronically steerable array.

Please refer to FIGURES 20 and 21 for large arrays using complementary pairs with optimum properties with respect to installation ease and also array factors providing a desired operational bandwidth. FIGURE 20 shows a vertically polarized array, of interlaced monopoles **48** and folded dipoles **49**, embodiment **50**. The monopoles which are individually mounted on appropriate mounting supports **51** extend vertically with respect to their mountings from the ground plane **52**. The monopoles **48**, fed at the apex bottoms, are positioned in substantially the same plane as the folded dipoles **49** which are mounted in a common plane on a mount structure **53** of conventional nature. The folded dipoles **49** are fed at the cross points **54**, detail not shown. Further, it should be noted that the monopole **48** and the folded dipole **49** elements are staggered vertically to minimize any existing detrimental effects of mutual coupling as with the embodiment of FIGURE 19. Further, the elements in a substantially common plane are spaced approximately 0.1λ, of frequency bandwidth center frequency, from a reflector screen **55** of relatively large conventional construction mounted to extend between vertical towers **56** and **57**. At high frequency, with a proper ground radio system excellent low angle coverage is obtained with this antenna over a 5:1 frequency range.

The embodiment **58** of FIGURE 21 is a horizontally polarized broadside reflector array which also has staggered elements to provide maximum bandwidth without grating lobe formation. This embodiment allows close element spacing and uniform reflector illumination and provides approximately a 4:1 frequency range. In this embodiment the dipoles **59** and folded dipoles **60** are mounted on a common supporting structure **61** in substantially a common plane which is spaced approximately 0.1λ from reflector screen **62** mounted between vertical towers **63** and **64** mounted to extend vertically from the ground plane. Both the dipoles and folded dipoles of FIGURE 21 are fed at center element cross points **65** and **66**, respectively, detail not shown. With both embodiments **50** and **58**, the reflectors **55** and **62** result in a high front-to-back ratio, and a very low forward side lobe factor may be attained. These basic array module approaches may be extended to form broadside arrays of very high gain with the limit at high frequency generally being set by minimum tolerable beam widths.

If a reflector is not desirable, and low side lobes are not mandatory, then the endfire array of FIGURE 22 is a good antenna solution, although in this case the bandwidth is limited by the array factor to about an octave. With this embodiment, some gain optimization in side lobe control is possible with non-uniform spacing of complementary pair element groups. In the particular showing, three element groups **67** are of one longitudinal spacing over ground plane **68**, with the end element groups **69**, while of the same construction as element groups **67**, being more widely spaced along the same longitudinal line outwardly from the closest element group **67** than the spacing between element groups **67**. Because of the great extent in depth of this array, and resulting low effective elevation aperture, good low angle coverage is also provided. In each element group of this antenna array, a dipole **70** is mounted directly above a leg **71** of a folded monopole **72** by structural means not detailed. The dipole **70** of each complementary pair element group **67** and **69** is fed by a feedline **73** extended vertically through and insulated from the folded monopole leg **71** and through a portion of each dipole **70** to a center cross feed point **74**. The other legs **75** of each folded monopole **72** are fed at a lower conical apex feed end **76** at the ground plane **68**. It should be noted that in order for the two elements in each group to come down to the 50 ohm level of a 180 degree feed hybrid, a different impedance transformation network is required for each element having a transformation ratio of approximately 2:1 for the dipole **70** and 4:1 for the folded monopole **72**. Here again it should be noted that the elements are staggered inherently with the vertically stacked dipole and monopole construction employed.

The paracylinder antenna **77** for high frequency or very high frequency usage is shown in FIGURE 23 to employ an endfire monopole complementary pair element group **78** feed utilizing two spaced monopoles **79** and **80** fed through a 180 degree hybrid to their bottom conical apex feed ends **81** located at the ground plane **82**. The feed beam direction is from the monopole elements **79** and **80** toward the paracylinder parabolic arc reflector **83**. Reflector **83** is a relatively large structure provided with increasingly large spacing between wires **84** with increasing distance from the center of the paracylinder located approximately at vertical center reflector supporting tower **85** in the particular paracylinder reflector shown. Other towers **85A**, **85B**, **85C**, and **85D** are provided in increasing distances to each side from the reflector center mounting tower **85**. The increasingly larger wire spacings between wires **84** with increasing distance from the center tower **85** provides for controlled reflector **83** leakage with the outer portions of the reflector **83** becoming significantly effective only at the lower frequencies. The endfire monopoles **79** and **80** may be provided with guy wire installation support, not shown, in a conventional manner as required. This antenna feed system advantageously provides good illumination of the wide angle aperture while still having sufficient directivity to greatly minimize

gain variations due to feed mage interference. Furthermore, directive gains up to about 30 db are feasible at the high end of approximately a 4:1 operational bandwidth.

In the paraboloidal reflector antenna system embodiment **86** of FIGURE 24, a paraboloidal reflector **87** is provided with a dual complementary pair element group feed **88** consisting of two cross polarized endfire dipole complementary pair element groups to thereby be a system capable of providing all types of polarization. An advantage of this feed system over a log periodic structure in this embodiment is an almost constant phase center position through a wide frequency range of operation. It is an embodiment with a feed front-to-back ratio that can be improved by the addition of a small complementary pair element group reflector at the outer end of tube **89** with some increase in aperture blockage. The antenna **86** can provide very high gains at VHF and UHF with the upper limit being dictated by structural mechanical considerations. Depending upon the types of baluns used in and feedlines through tube **89**, and hybrids employed in the feed circuit, approximately a 5:1 bandwidth range is achievable in frequency ranging up to approximately 1 gc. (gigacycle). For S-band and C-band applications octave frequency range would be feasible as limited primarily by balum circuit bandwidth limitations. Feed of this antenna is with lines coming through the back of the reflector **87** through tube **89** to balum circuitry in the vicinity of the dual complementary pair element group feed **88** at the outer end of the tube **89**.

In FIGURE 25 a low-silhouette broadband fixed beam circular antenna array embodiment **90** is portrayed. This embodiment employs a plurality of endfire monopole complementary pair element groups **91** with each element group having a post-type reflector **92** associated therewith and in beam directional alignment with the monopoles **93** and **94** of the respective element groups **91**. All the element groups **91** are oriented in substantially the same beam directional alignment and are arranged in, generally, a circular array of a multiplicity of element groups above ground plane **95**. While this post-type reflector equipped multiple complementary pair group antenna array does not provide as much group directivity as a large flat reflector embodiment, the array factor does have a reasonably good front-to-back ratio. It is an antenna array embodiment having a large effective aperture both in azimuth and elevation and also good elevation beam steering potential. Azimuth steering with this embodiment is also possible through a limited angular range as limited by group pattern limitations. It is an antenna imposing large area requirements that may be justified when low antenna array height is desired along with ease feeding of the end-fire monopoles through the ground plane **95**.

The electrically steerable complementary pair element group Wullenweber type antenna embodiment **96** of FIGURE 26 is an example of a relatively simple antenna structure capable of being steered electromechanically or electrically through an arbitrary range in azimuth, dependent upon the percentage of a full circle through which the reflector **97** and endfire complementary element groups **93** are provided. Each endfire complementary element group **98** includes endfire monopoles **99** and **100** in longitudinally spaced relation on radials and spaced outwardly from circular reflector **97** with the radials being radials relative to substantially the geographic center of the circular reflector **97**. This antenna approach is most economically efficient for a full circle embodiment such as shown particularly when a full 360 degrees of azimuth steering electronic feeding control is required, such as for high frequency direction finding. Here, again, this embodiment employs endfire monopoles advantageously fed through or at the ground plane **101**. The antenna reflector **97** is shown to be a multi-tower **102** supported screen or depending wire type reflector. It should be noted that horizontally polarized complementary pair element groups could be used in a Wullenweber antenna system in place of the endfire monoploe complementary element groups shown in the antenna embodiment **96** of FIGURE 26. Further, the bandwidth of the monopole array can be extended by vertically stacked low frequency elements. An antenna system is thereby provided wherein the entire high frequency spectrum may be covered in one structure with, however, no elevation steering possible. A further notable advantage of such complementary pair element group equipped Wullenweber-type antennas is that low minor lobe levels are achieved.

The circular antenna array embodiment **103** of FIGURE 27 is equipped with endfire monopole complementary pair element groups **104** aligned on radials emanating from substantially the same image point. It has inner endfire monopoles **105** substantially on a circle, the outer endfire monopole elements **106** on a circle concentric with the circle of the inner monopoles **105**, and with the two concentric point rings spaced a distance equal to substantially a quarter of a wavelength of the operational bandwidth center frequency. Here, again, in this embodiment the endfire monopoles are advantageously fed at or through the ground plane **107**. This embodiment has improved operational side lobe conditions and allow 360 degrees azimuth steering over approximately a 3:1 frequency range. A further modification, not shown, is an extension of the circular array approach of FIGURE 27 to an additional dimension in expanding an array to a spherical array with hemispherical operational coverage.

If azimuth steering is required to approximately ±50 degrees, the broadside reflector **108** endfire complementary pair element group antenna array embodiment **109** of FIGURE 28 is very efficient structurally and is operationally an economical antenna. This employs a multiplicity of endfire monopole complementary pair element groups with one endfire element **110** of each group positioned substantially along a line approximately 0.1λ of the operational bandwidth low frequency from the reflector **108** and parallel thereto. The other elements **111** of the element groups are in longitudinal alignment along a line substantially parallel to the line of the endfire elements **110** and substantially parallel to the reflector **108** and spaced an additional distance outwardly relative to the reflector **108** from the inner elements **110** approximately equal to 0.125λ low and 0.375λ high frequency of the operational frequency bandwidth range. Furthermore, the element groups are spaced from one another in the range of from 0.2λ low to 0.6λ high frequency of the operational frequency bandwidth. Here, again, the endfire monopoles are advantageously fed at or through the ground plane **112**, detail not shown.

Another interesting complementary pair element group hybrid system feed antenna embodiment **113** is shown in FIGURE 29 to be a self-supporting conductive material cylinder **114**, miniature slot **115** and dipole **116** complementary pair element group antenna. The enclosed cavity chamber **117** of generally arcuate shape enclosed by conductive material defining such a cavity encloses dielectrical material fill **118** of ceramic or a plastic dielectric material completely filling the cavity with the exception of the coaxial inner stub feed **119** from coaxial line **120**. The outer coaxial sheath of coaxial line **120** is connected to the conductive material forming chamber **117**. The other coaxial line **121** passes through the interior of the antenna cylinder **114** to extend through a cylinder wall port **122** and interiorly upward through the lower section **123** of dipole **116** to a connection of the outer sheath of coaxial line **121** with the upper conical apex feed end of the lower section **123**. The inner line of coaxial cable **121** is connected to the lower conical apex feed point of the upper section **124** of dipole **116**.

The vertical dipole **116** in this embodiment is fed 90 degrees out of phase with slot **115**, a feed phasing which may be accomplished with a 180 degree hybrid, such as hybrid **37** of FIGURE 1 and FIGURE 4 and other figures in the case, as part of a feed network including additional phasing circuitry. The additional phasing circuitry could be provided such as by making one of the coaxial lines **120** and **121** a quarter of a wavelength longer than the other, as had been accomplished with the coaxial lines **35** and **36** with reference to FIGURE 4 and the embodiment of FIGURE 3. Dipole **116** may be mounted on cylinder **114** as by bracket **125** of non-conductive material in a conventional manner. In this antenna structure, the slot is made vertically physically shorter than half a wavelength, a factor eliminating any danger of elevation pattern lobing. It is an antenna useful for circular polarized UHF transmission that may employ adjustable position cover plates and inductive loading holes, detail not shown, at opposite ends of slot **115** for tuning as may be desired. While one element complementary group with the hybrid feeding system of this embodiment is shown on the cylinder **114**, a multiplicity of such complementary pair element groups could be arranged around the circumference of cylinder **114** to provide desired azimuth coverage and, further, several of the circularly polarized groups may be stacked vertically to increase gain. While practically any reasonably desired level of gain and azimuth coverage may be thereby attained, such increase in the numbers of the complementary groups particularly with the stacking thereof is accomplished at some expense in efficiency in the individual element groups.

Thus, it may be seen that this invention provides very effective and efficient antenna systems utilizing various 180 degree hybrid feed complementary pair element group embodiments useful through extended frequency bandwidth in high frequency applications. Various high frequency antenna embodiments set forth would be particularly useful in fixed and mobile communications systems, in direction finding antenna usuage such as for air traffic control systems, and high quality broadcasting relay lengths, and in over-the-horizon radar installations. Furthermore, there are many uses to be found with various embodiments spanning VHF and UHF frequency ranges and to even higher frequency ranges. Further, various embodiments presented, with a constant phase center and constant radiated power with varying efficiency, allow for transmission of narrow pulses with a minimum of dispersion. Various other applications include space tracking, spectrum surveillance and radio astronomy.

The complementary pair element groups in various antenna systems, particularly in the broadside and endfire versions are valuable new broadband radiators for both fixed beam and steerable beam antennas as major families. The fixed beam antenna family may be sub-divided further into focusing reflector equipped antennas such as paracylinders and paraboloids, circular arrays, broadside reflector arrays, and endfire arrays. The electically steerable antennas may be divided as indicated by various illustrated and suggested embodiments, for example, into circular and spherical arrays and into linear and planar arrays. Thus, a systematic classification is evolved placing the various antenna configurations of both the major families (fixed beam and steerable beam antennas) into various categories, depending on the type of complementary pair element group embodiment used, and whether or not a reflector is embodied and so on, and would therefore appear to be a major advance in the state of the art of broadband antennas. Further, this is all accomplished with complementary pair element group element spacing, in the various embodiments, equal to less than approximately 0.7λ of the operational bandwidth center frequency. This is a spacing limitation necessarily imposed to effectively achieve mutual radiation coupling required between paired elements in providing the complementary pair element groups.

Whereas, this invention is here illustrated and described with respect to specific embodiments thereof, it should be realized that various changes may be made without departing from the essential contribution to the art made by the teachings hereof.

I claim:

1. In an antenna system, a complementary pair element group having complementary impedance characteristics with element spaced less than approximately 0.7 wavelength of the operational bandwidth center frequency so as to be effectively radiation mutually coupled; a feed network between each of the elements of the complementary pair of elements; and with the feed network including a "Magic T" hybrid junction having a difference port terminated in an impedance substantially equal to the characteristic impedance of the hybrid difference port and having two additional ports connected to respective elements of the complementary pair of elements, with the two connecting cables matched to the two additional ports, whereby the reflection coefficients cancel.

2. The complementary pair element group of claim **1**, wherein the "Magic T" hybrid junction is a 180 degree hybrid junction; and the two elements of the complementary pair element group are additive in radiation characteristics primarily in one direction.

3. The complementary pair element group of claim **2**, wherein the group is an endfire complementary pair element group mounted above a ground plane; and means feeding the two elements of the endfire complementary pair in the vicinity of the ground plane.

4. The complementary pair element group of claim **3**, wherein an element of the pair of elements is provided with a top loading extended planar end.

5. The complementary pair element group of claim **3**, wherein the two additional ports of the 180 degree hybrid junction are connected to the respective elements through coaxial lines; and with one of the two coaxial lines substantially a quarter of a wavelength of the operational bandwidth center frequency longer than the other coaxial line.

6. The endfire complementary pair element group of claim **5**, wherein a planar reflector is provided perpendicular to the longitudinal axis plane of the endfire paired elements; with said planar reflector also substantially parallel to the axis of each of said endfire paired elements; and with the reflector having a smaller spacing from the closest element than the spacing between the paired elements.

7. The complementary pair element group of claim **2**, wherein the complementary pair element group includes, a vertical dipole and folded dipole mounted in spaced relation from a planar reflector element and above a ground plane.

8. The vertical dipole and folded dipole complementary pair element group of claim **7**, wherein the feed connections are through impedance transforming baluns at the mounting of each respective element; an extended element top is provided on the folded dipole; and the elements are staggered vertically to minimize any existing detrimental effects of mutual coupling.

9. The complementary pair element group of claim **2** wherein a plurality of complementary pair element groups is used in a vertically polarized antenna array including interlaced monopoles and folded dipoles; with the monopoles mounted to extend vertically from a ground plane in substantially a common plane; the folded dipoles being mounted in complementary pair element group relation with the respective monopoles in substantially the common plane of the monopoles; and a reflector screen spaced approximately 0.1 wavelength of the operational bandwidth low frequency from the common plane of the monopoles and folded dipoles.

10. The complementary pair element group of claim **2** wherein a plurality of complementary pair element groups is used in a horizontally polarized antenna array including interlaced monopoles and folded dipoles; with the monopoles and the folded dipoles being mounted in a complementary pair element group relation in substantially a common plane; and a reflector screen spaced approximately 0.1 wavelength of the operational bandwith low frequency from the common plane of the monopoles and folded dipoles.

11. The complementary pair element group of claim **2**, used in plurality in an endfire array as a multiplicity of complementary pair element groups; with, in each complementary pair element group, a folded monopole mounted to extend above a ground plane common of the whole antenna array; a dipole mounted above a leg of the folded monopole of that complementary pair; and with a feedline extended vertically through a folded monopole leg to the dipole.

12. The complementary pair element group endfire array of claim **11**, wherein the complementary pair element groups are in substantially aligned relation with a plurality of groups having one spacing, and with terminating end groups having a greater spacing from adjacent complementary pair element groups.

13. The complementary pair element group of claim **2**, wherein an endfire monopole complementary pair element group feed is provided for a paracylinder reflector equipped antenna with the complementary pair element group feeding toward the reflector.

14. The paracylinder antenna of claim **13**, wherein the reflector is a parabolic arc reflector built up of reflective elements; with increasingly large spacing between reflective elements of the parabolic reflector with increasing distance to each side of the center of the parabolic arc reflector so that outer portions of the reflector become significantly and increasingly effective only at the lower frequencies.

15. The complementary pair element group of claim **2**, wherein dual complementary pair element groups are constructed as two cross polarized endfire dipole complementary pair element groups in a feed for a paraboloidal reflector antenna.

16. The complementary pair element group of claim **2**, used in plurality in the form of endfire monopole complementary pair element groups in a low silhouette broadbeam-fixed-beam generally circular antenna array; with each element group being provided with a post-type reflector positioned in operational association therewith and in beam directional backing alignment with the respective endfire monopole complementary pair element groups.

17. The complementary pair element group of claim **2**, also including a Wullenweber-type antenna reflector presenting an effectively circularly arcuate electronic radiation reflective surface; and with endfire monopole complementary pair element groups positioned substantially on radials of the circularly arcuate reflector image center and outwardly from the reflector.

18. The complementary pair element group of claim **2**, used in plurality in the form of endfire monopole complementary pair element groups in a circular antenna array with the inner endfire monopoles of the multiplicity of element groups on a common circle; and the outer endfire monopole elements on a circle concentric with the circle of the inner monopoles; and with the two concentric circles having a spacing substantially equal to a quarter of a wavelength of the operational bandwidth frequency; and with the endfire monopoles fed substantially at the ground plane of the antenna array.

19. The complementary pair element group of claim **2**, wherein a broadside endfire complementary pair element group antenna array employs a multiplicity of endfire monopole complementary pair element groups with one element of each group common to a line approximately one-tenth of a wavelength of a low frequency of the operational frequency bandwidth range from a reflector; and the other elements of the element groups substantially common to a second line also parallel to the reflector and spaced a predetermined additional distance outwardly relative to the reflector from the inner elements approximately equal to 0.125 wavelength of a bandwidth range low frequency and to 0.375 wavelength of an operational frequency bandwidth high frequency.

20. The complementary pair element group of claim **2**, wherein a miniature slot and dipole complementary pair element group is used in an antenna cylinder contained slot and dipole complementary pair element group antenna system; with the dipole mounted outwardly from the cylinder, and displaced to one side from the slot opening in the cylinder wall.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,449,751 June 10, 196

Klaus G. Schroeder

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 1, line 17, "imepance" should read -- impedance --. Column 3, line 11, "reactant" should read -- reactance --. Colum 4, Equation (1), should appear as shown below:

$$Z_\Sigma = \frac{n_\Sigma^2\left(\frac{N_1{}^2}{Z_1} + \frac{N_1{*}^2}{Z_1{*}} + \frac{N_\Delta{}^2}{Z_\Delta}\right)}{(N_1+N_1{*})^2 \quad \frac{1}{Z_1Z_1{*}} + \frac{N_\Delta{}^2}{Z_\Delta} \quad \frac{1}{Z_1} + \frac{1}{Z_1{*}}}$$

Column 4, Equation (2), should appear as shown below:

$$Z_\Sigma = \frac{\frac{1}{Z_1} + \frac{1}{Z_1{*}} + \frac{2}{Z_\Delta}}{\frac{2}{Z_1Z_1{*}} + \frac{1}{Z_\Delta}\left(\frac{1}{Z_1} + \frac{1}{Z_1{*}}\right)}$$

Column 5, line 63, after "forward" insert -- element --. Column 6 line 9, "is" should read -- it --; line 14, "that" should read -- the --; line 61, "This" should read -- Thus --; line 70, "approximately" should read -- approximating --. Column 7, Equati (1A) should appear as shown below:

$$Y_\Sigma = \frac{(N^1{}_\Sigma)^2\left((N_1+N_1{*})^2\, Y_1Y_1{*} + N_\Delta{}^2\,(Y_1+Y_1{*})\, Y_\Delta\right)}{(N_\Sigma)^2\left(N_1^2Y_1 + (N_1{*})^2\, Y_1{*} + N_\Delta{}^2\, Y_\Delta\right)}$$

Column 12, line 1, "mage" should read -- image --. Column 13, line 3, "monoploe" should read -- monopole --; line 25, "allow" should read -- allows --; line 39, after "along" insert -- a --; line 63, after "inner" insert -- line --. Column 14, line 34, "width" should read -- widths --. Column 16, line 62, before "frequency" insert -- center --.

Signed and sealed this 19th day of May 1970.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
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Commissioner of Patent