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Ross et al.

[11] **3,714,655**

[45] **Jan. 30, 1973**

[54] ARRAY ANTENNA SIGNAL PROCESSING SYSTEM

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[21] Appl. No.: **76,937**

[52] **U.S. Cl.** .....**343/100 R**, 343/100 SA, 343/854

[51] **Int. Cl.** **H01q 3/26**

[58] **Field of Search** .....343/100 R, 100 SA, 854

[56] **References Cited**

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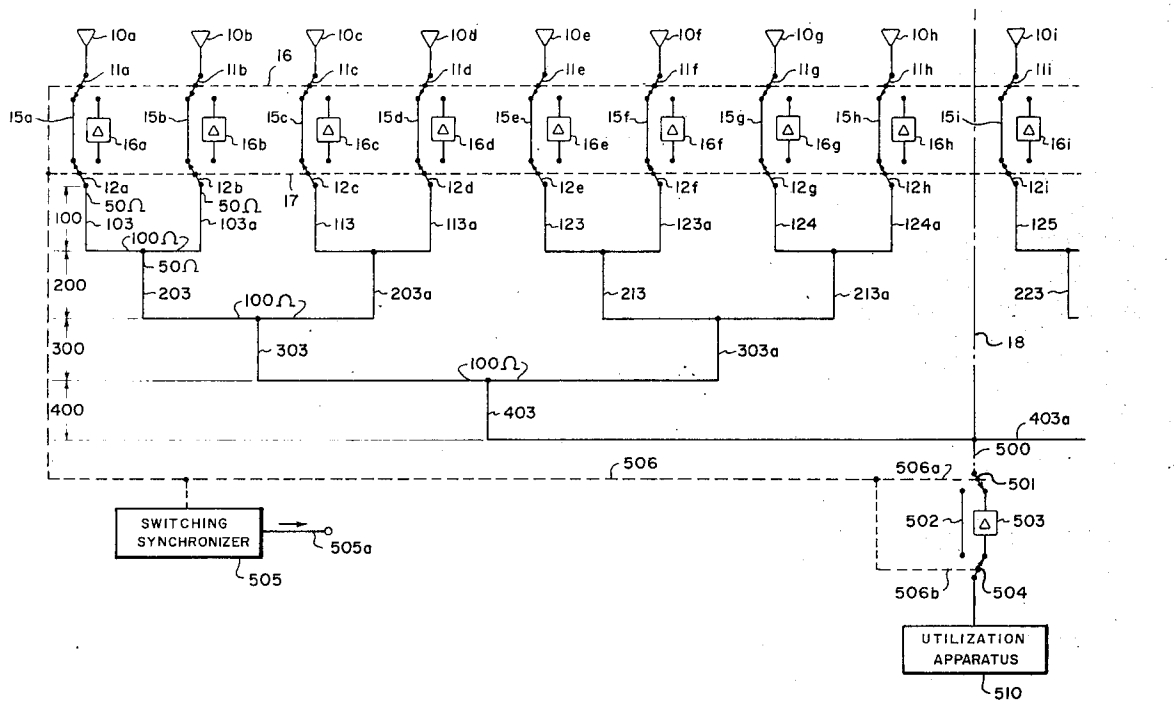
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Assistant Examiner—G. E. Montone
Attorney—S. C. Yeaton

[57] **ABSTRACT**

A electromagnetic energy coupling network for reciprocally processing or combining electromagnetic energy flowing in pluralities of transmission lines is disclosed. The coupling element is a multiple port transmission line junction associated with tapered transmission lines and efficiency transferring energy inputs on such lines into a wave flowing only from a single output port. The network may be employed individually or in multiple quantities as an element in complex coupling tree network matrices for the processing of individual impulse signals received by the elements of an antenna array. In application in such signal combining tree matrices, means are provided in the matrix depending upon inherent properties of the coupling element for degrading the adverse effects of internally generated spurious signals.

6 Claims, 11 Drawing Figures



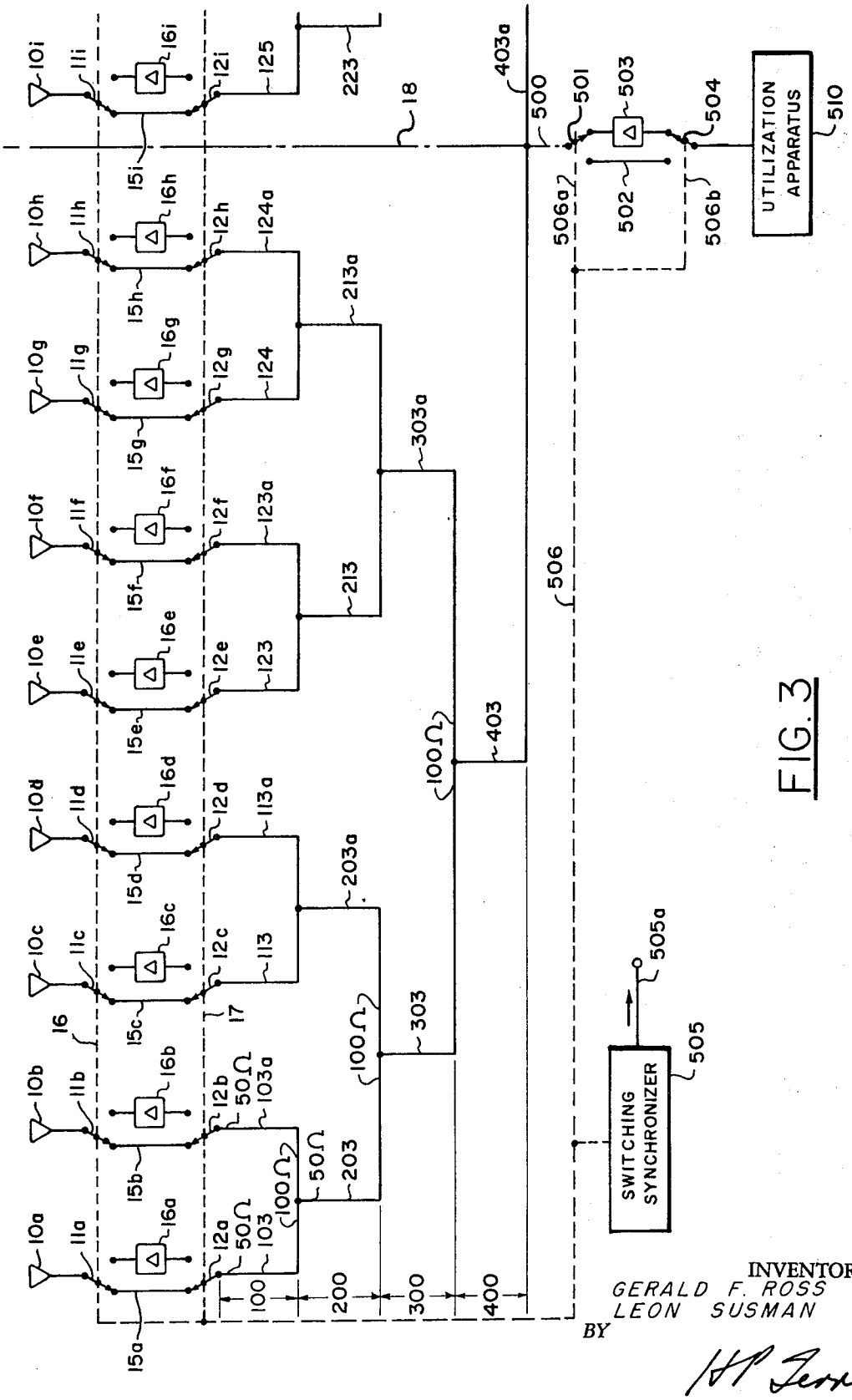


FIG. 3

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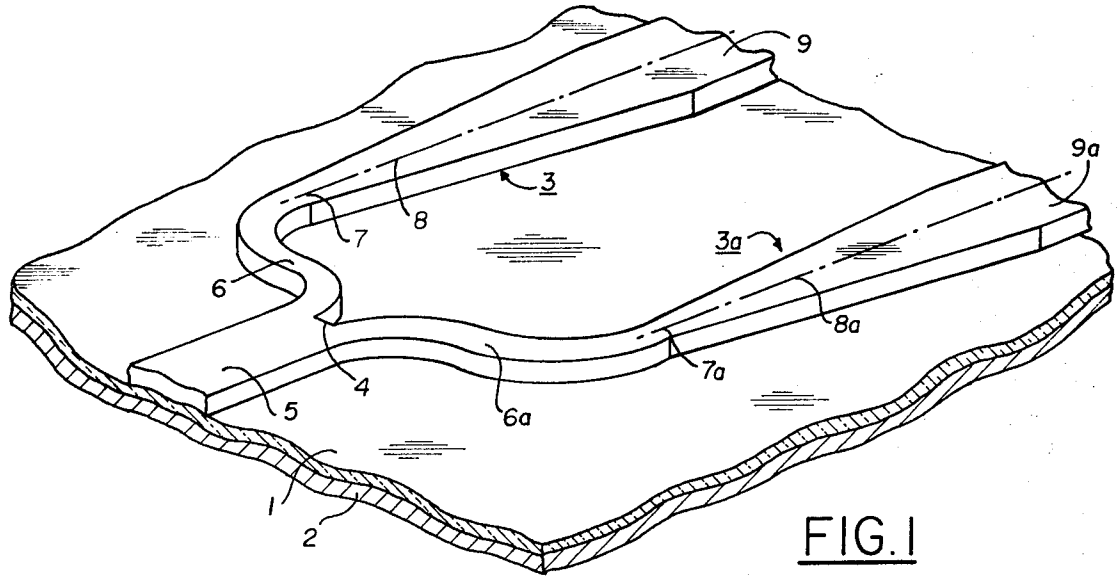


FIG. 1

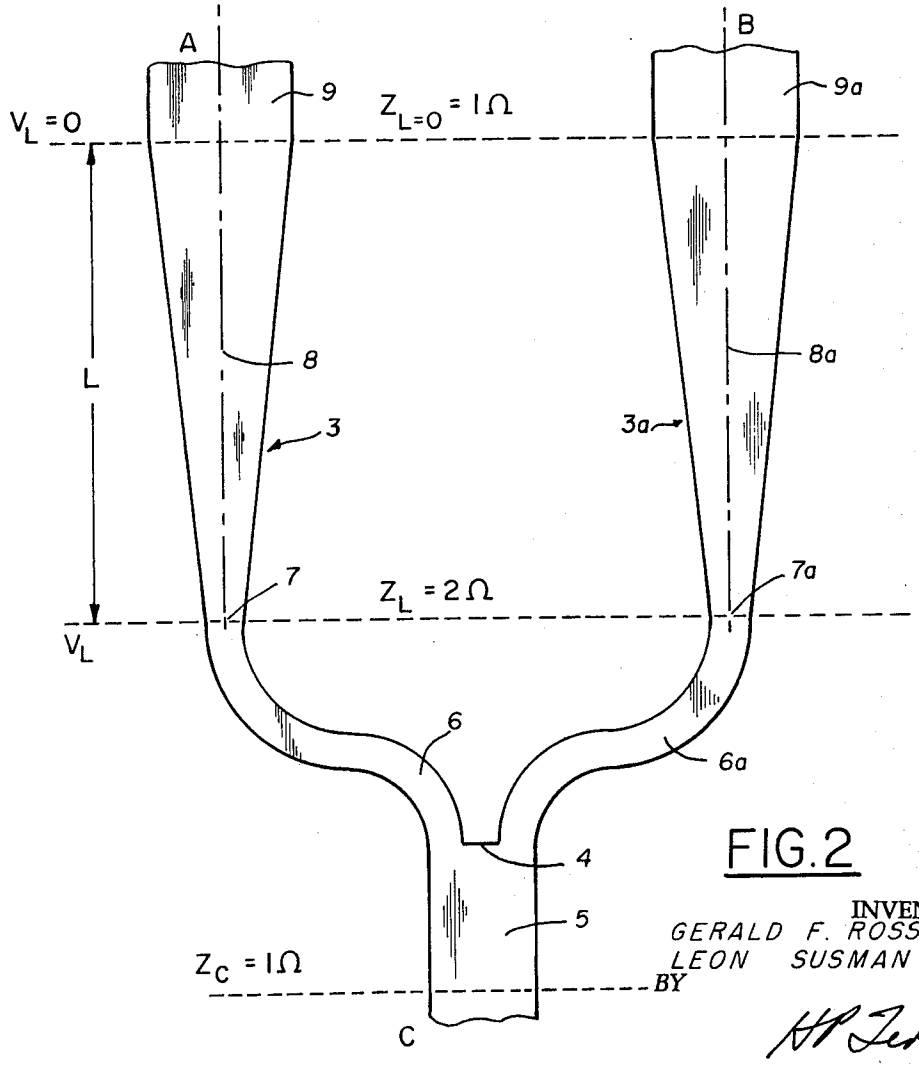


FIG. 2

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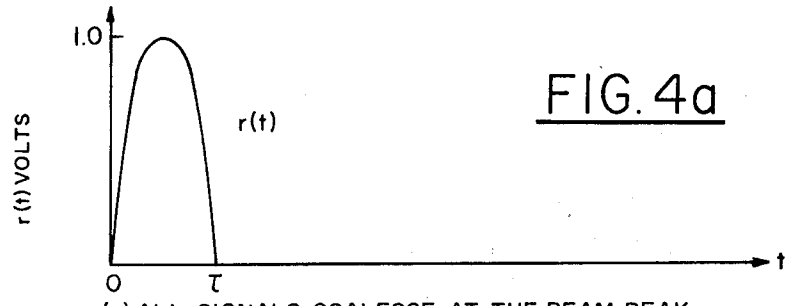


FIG. 4a

(a) ALL SIGNALS COALESCE AT THE BEAM PEAK.

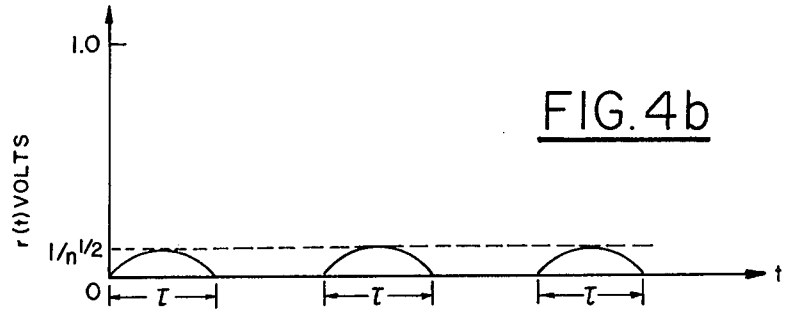


FIG. 4b

(b) RESPONSE OFF ANGLE.

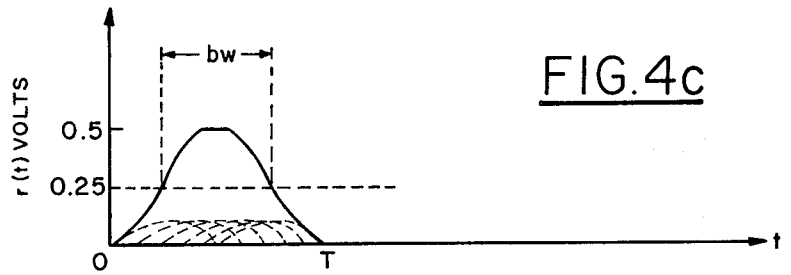


FIG. 4c

(c) DEFINITION OF BANDWIDTH

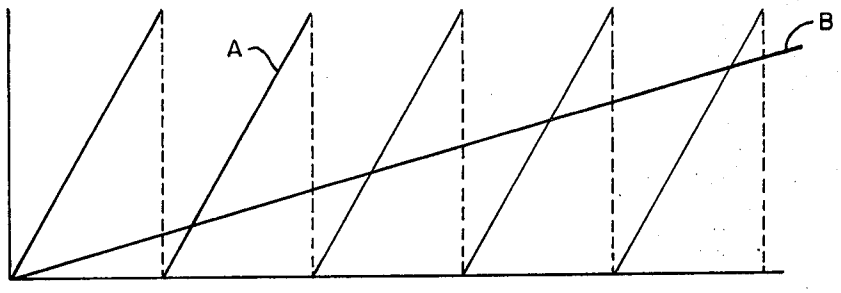
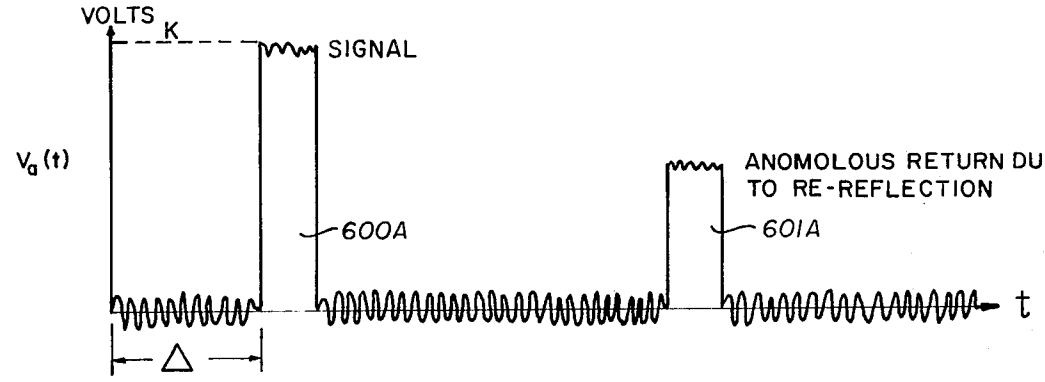


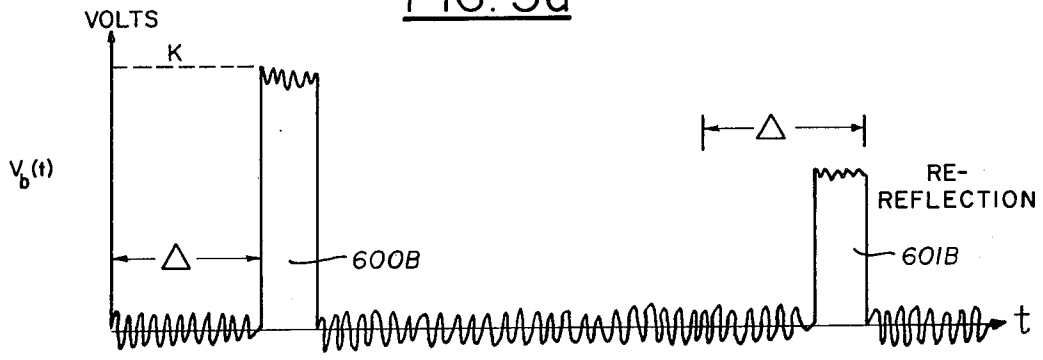
FIG. 7

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OUTPUT WAVEFORM-MODE A-DELAY Δ SECONDS IN THE OUTPUT LINE 500.

FIG. 5a



OUTPUT WAVEFORM-MODE B- DELAY Δ SECONDS IN EACH ANTENNA ELEMENT LINE.

FIG. 5b

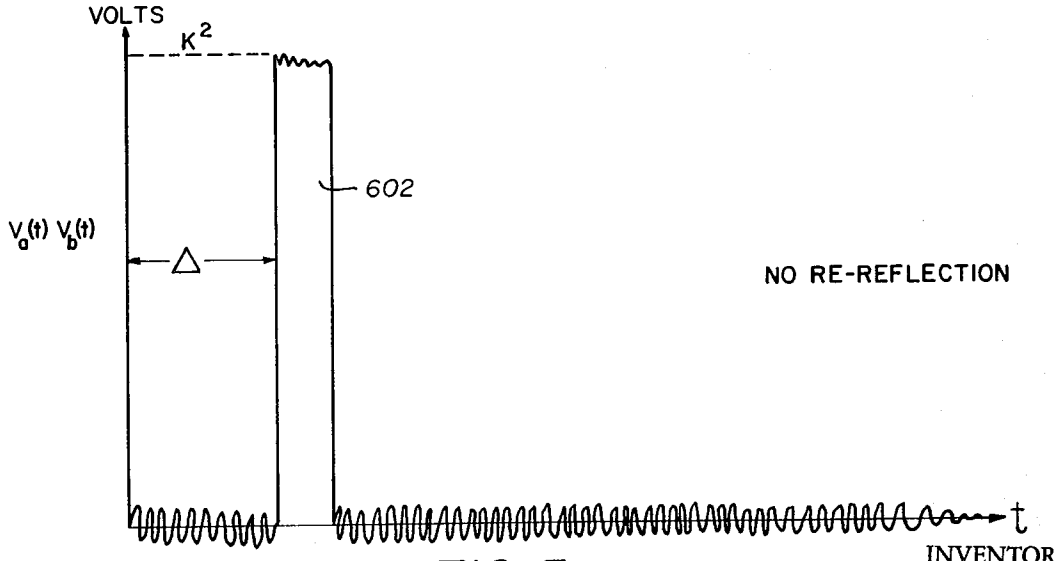


FIG. 5c

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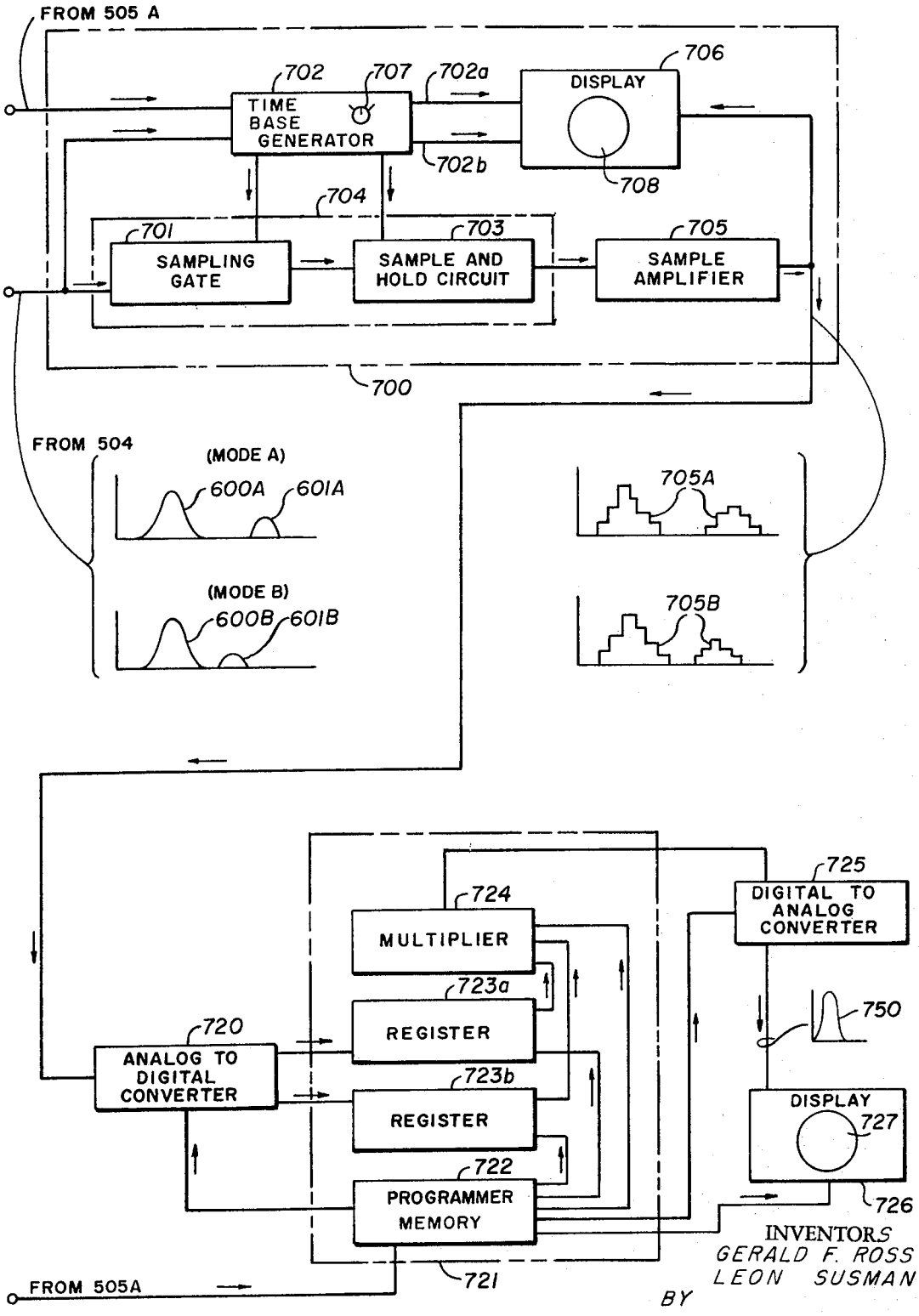


FIG.6

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ARRAY ANTENNA SIGNAL PROCESSING SYSTEM

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention pertains to combining networks or tree matrices for combining or reciprocally processing electromagnetic waves flowing in pluralities of transmission lines and to means for reducing spurious responses therein.

2. Description of the Prior Art

Combining or processing networks for efficiently combining coherent electromagnetic energy, especially such energy when of impulse duration, are recently of increasing interest for processing electromagnetic signals collected by multiple-collector array antennas. They are of interest in this and other such applications wherein a plurality of coherently applied signals is processed by combining networks to yield a maximum signal at a single output port. Generally, combining networks of the past have not had capabilities of efficient operation over a multiple-octave instantaneous frequency band when excited by input signal wave forms of sub-nanosecond duration.

The prior art has recognized that, in order to construct a coupling network or matrix for combining or processing a plurality of coherent signals, a coupling element is required having special properties. The element may, for example, be a three-port junction and it must maximize the signal output at one of its ports; i.e., it must with maximum efficiency transfer any energy input at two of its ports to a third or output port. Only this behavior results in the desired minimum over all network distortion or dispersion.

Known junctions have not filled the described need. For example, known types of high frequency or microwave directional couplers introduce time-domain distortion. To use such coupler devices, there must generally be tolerated a compromise trade off of efficiency against distortion. One type of directional coupling network minimizes distortion, but requires an impractical number of coupling elements. Attempts to use other four-port biconjugate network elements in combining or signal processing networks or matrices have generally resulted in poor efficiency and severe dispersion.

SUMMARY OF THE INVENTION

The invention pertains to novel high frequency or microwave transmission line coupling networks or matrices and to applications thereof. The invention utilizes a bilateral elemental coupling device which may be used in multiple quantities in tree matrices for forming complex coupling system networks. The elemental coupling device is a three port transmission line junction employing specially tapered input and output transmission lines associated with a tee junction. Signal energy entering the two symmetric ports of the junction is transferred in total to a wave emanating from the third port, and vice versa.

The coupling device has use in coupling matrix or tree network systems for application in novel sub-nanosecond antenna arrays in which the contributions of a number of effectively discrete but coherent sources are summed by the coupling tree matrix according to a novel technique. An output pulse from a single port of the matrix or network represents a substantially perfect summation of the total energy of the plurality of effectively discrete sources. The inherent properties of such sub-nanosecond matrices are employed with switching, delay, and signal amplitude multiplication means for substantially eliminating the effects of signals spuriously generated within the matrix.

While the invention is illustrated as being employed in a form of an integrated circuit known as planar microstrip transmission line, it is to be understood in the following discussion that other types of transmission lines, such as are commonly used with planar dielectric substrates, may also be used in demonstrating the invention. Thus, the invention may be employed with balanced strip, suspended substrate, slot line, H-guide, or the coplanar types of transmission lines. While the discussion which follows is in terms of use of the invention with microstrip or strip transmission lines, it may also readily be used with other types of transmission lines, including those mentioned above.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an isometric view, partly in section, of an embodiment of the coupling element employed in the invention.

FIG. 2 is a plan view of the coupler element of FIG. 1 used in explaining its operation.

FIG. 3 is a circuit diagram illustrating a novel application of the coupler element in an antenna array signal processing system.

FIGS. 4 and 5 are graphs used in explaining the operation of the apparatus of FIG. 3.

FIG. 6 is a block diagram showing in detail parts of the processing system of FIG. 3.

FIG. 7 is an explanatory graph.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In FIG. 1, there is shown a planar microcircuit useful at microwave or very high frequencies as a bilateral electromagnetic wave transmission line energy coupler circuit. The circuit shown represents a fundamental transmission line coupling network concept which may be used according to the invention as a basic element in complex coupling networks or matrices and elsewhere.

The transmission line device of FIG. 1 comprises at least a dielectric substrate 1 to one surface of which a relatively thin conductive ground sheet 2 may be bonded in any well-known manner. For example, the ground sheet 2 may be formed on one surface of the dielectric substrate 1 by evaporation of a suitable metal in a vacuum chamber from a heated source for distilling the desired conductive metal or by chemical electroplating or by other known metal plating methods.

The transmission line opposite ground plate 2 comprises, for example, planar or microstrip transmission line elements bonded to the second or upper surface of substrate 1. The transmission line system on the upper surface of substrate 1 may be bonded to substrate 1 by well known methods, including methods of the type employed to generate and bond the ground sheet 2.

The planar microstrip circuit of FIG. 1 consists of a three-port transmission line junction having properties which will be further discussed. The three-port junction has symmetric arms 3 and 3*a*, both conductively joined

via a coupling region 4 to a single planar transmission line 5. It is observed that branch lines 3 and 3*a* stem from the mutual coupling region 4, following oppositely directed doubly-arcuate segments 6 and 6*a*. Segments 6 and 6*a* form smoothly curved transmission paths which ultimately become substantially parallel to the single transmission line 5, being conductively continued from the point where parallelism is reached at junctions 7 and 7*a* by tapered transmission line segments 8 and 8*a* to further parallel transmission line sections 9 and 9*a*. It is to be understood that the parallel relation between line segments 5, 9, and 9*a* is one of convenience for use in many applications, but that other angular relations between these line segments are more convenient for use in other applications.

Sections 9 and 9*a* have widths transverse to the directions of energy propagation substantially equal to the corresponding width of transmission line 5. The branch transmission line section including doubly arcuate sections 6 and 6*a* has, however, a lesser width than line segments 5, 9, and 9*a*. The tapered sections 8 and 8*a* have non-parallel sides adjusted so as smoothly and continuously to join section 6 to section 9 and section 6*a* to section 9*a*, respectively.

Referring still to FIG. 1, it should be apparent that it is possible to extend dielectric sheet 1 and ground plate 2 in the direction of transmission line 5 so as to accommodate an extension of the latter or to support additional active or passive high frequency or other circuits in any combination desired to interact with the elements shown in FIG. 1. Likewise, substrate 1 and ground plate 2 may be extended in any desired direction to support additional active or passive circuit elements in any combination desired to interact with transmission lines 9 and 9*a*.

FIG. 2 is a simple outline only of the microcircuit bilateral coupler circuit shown in FIG. 1, as will readily be seen by comparison of the two figures. Corresponding parts have therefore been labelled with corresponding reference numerals. The purpose of FIG. 2 is to enable explanation of one theory of operation of the coupler network of FIG. 1.

Toward understanding the latter, it should be observed that the character of the tapered wave guide sections 8 and 8*a* is important to its successful operation. For example, the transient behavior of such tapered transmission lines has been found to include a minimum of distortion, providing that the length L of each tapered section is great compared to the quantity $c\tau$, which quantity is the product of an input transient or impulse duration τ and the speed of light c, provided also that the change in impedance level from the high impedance end of the tapered section to the other is less than three to one. The parameter $c\tau$ has been established in the field of microwave transient signal research as a useful parameter for identifying the behavior of transmission line elements exposed to short duration electromagnetic signals. It has been reported in the literature as being of interest in the qualitative evaluation of signal distortion in terms of the length of a tapered transmission line. For example, if $c\tau$ is very small compared to the length of a tapered line, only a negligible distortion will be suffered by impulse signals traversing the tapered line.

The parameter $c\tau$ is also of interest in qualitatively defining the character of the junction region 4 where branch lines 6 and 6*a* join line 5. Here, for transmission of a relatively undistorted transient or impulse signal, the general area commonly regarded as the junction region needs to be great compared to $c\tau$. The region 4 then behaves like a simple resistive discontinuity to transients, rather than having distributed dispersive characteristics that cause signal distortion. With $c\tau$ very small by comparison, the dispersion or smearing of a very short pulse passing through region 4 is small compared to τ. While the junction 4 itself is not readily defined in purely geometrical terms, it is readily in terms of the electromagnetic fields propagating across the junction. In essence, it has been described as involving an area centered on junction 4 where there are TEM and other propagation modes present. Departure a short distance from the actual junction region discovers the presence only of the TEM mode fields normally associated with propagation in planar microcircuit lines.

Assume, for instance, that a unit volt signal is incident at port A associated with branch 3 of the coupler of FIG. 2. Such a signal will propagate into planar strip line section 9 in substantially the TEM mode. When the unit signal begins to propagate into the tapered line section 8, its peak voltage value must increase in magnitude as energy must be conserved. For example, it can readily be shown that the voltage amplitude at any distance L from the end 7 of tapered section 8 is:

$$V_L = V_{L=0}\sqrt{Z_L/Z_{L=0}} \tag{1}$$

For example, if:

$$Z_L = 2Z_{L=0} \tag{2}$$

(e.g., $Z_{L=0}=50$ ohms, $Z_L=100$ ohms) then:

$$V_L = \sqrt{2}V_{L=0} \tag{3}$$

Thus, the impulse or transient signal approaching the tee junction 4 on the reversing arcuate path of transmission line 6 has increased in magnitude by the factor $\sqrt{2}$.

It can readily be shown that the reflection coefficient at junction 4 for a signal traveling in line 6 toward it is real and is given by:

$$\Gamma = Z - Z_0/(Z + Z_0) \tag{4}$$

For the indicated $Z_{L=0}$ and Z_L values, $\Gamma = -0.5$. It follows that the voltage V_t transmitted from junction 4 toward the output port C and also toward port B associated with transmission line 3*a* is given by:

$$V_t = (1 + \Gamma) \tag{5}$$

or:

$$V_t = V_L/2 \tag{6}$$

In a similar manner, it will be seen that a unit voltage signal incident at port B associated with branch 3*a* of the bilateral coupler device produces a voltage V_t transmitted from junction 4 toward the output port C and also toward port A associated with line 3, this voltage V_t also being given by equation (6).

Accordingly, if operating generators of coherent signals are placed at ports A and B equidistant from transmission line junction 4, the total voltage V_t contribution from both sources A and B at the output port C is predicted from equations (1) and (6) to be:

$$V_T = V_L = \sqrt{2}\,V_{L=0} \tag{7}$$

Thus, the net voltage at output port C has been increased by a factor of $\sqrt{2}$.

It also follows that under the circumstances cited above, all of the energy input at ports A and B is delivered to output port C; i.e., the coupler network is 100 percent efficient under such operational conditions. In other terms, the transmitted voltage V_t due to a generator at port A which appears from equation (6) to be transmitted toward port B is met at junction **4** by an identical but opposite reflected voltage due to the generator at port A. Energy flow toward ports A and B cannot occur, these being forbidden paths when $Z_L = 2$ $Z_{L=0}$. The network is 100 percent efficient, providing signals from ports A and B arrive at junction **4** simultaneously.

FIG. **3** represents a novel application of the reciprocal energy combining or dual branch network of FIGS. **1** and **2** in a system employing a signal processing tree matrix of such networks for the purpose of providing a sub-nanosecond antenna array having high directivity, narrow effective beam width, and high efficiency. Such antenna arrays effectively focus incoming radiation by use of an array of collector elements and of combining means for coherently adding the energy received from a specific direction in space by each collector element. Energy coming from other directions adds to produce signals of lower amplitude, as will be seen. The antenna array of FIG. **3** performs the desired summation by use of a plurality of the special energy combining or dual branch networks of FIGS. **1** and **2**, since such networks introduce a minimum of time domain distortion and do not attenuate the antenna response.

In the discussion of the apparatus of FIG. **3**, reference will be had to detection of targets relative to one plane only, as it is apparent to those skilled in the antenna art that principles and apparatus useful in scanning in space about one axis may equally well be separately or simultaneously applied about a second scan axis. Further simplification of the drawing has been made by showing in FIG. **3** substantially only one half of the energy collector array and tree network, it being understood that similar halves of the antenna array and tree network are formed on each side of the vertical dash-dot line **18** which extends vertically above the tree network output transmission line **500**.

FIG. **3** is intended to illustrate an antenna array of p energy collectors **10***a*, **10***b*, . . . , **10***p*, of which collectors **10***a* and **10***h* are shown in the figure as forming half of the total antenna array. Collectors **10***a*, **10***b*, . . . , **10***p* are at any one instant of time connected through switch arrays **11***a*, **11***b*, . . . , **11***p* and **12***a*, **12***b*, . . . , **12***p* to the respective input leads of the tree network.

The energy combining bilateral tree network comprises a tree matrix with four successive tiers or stages **100**, **200**, **300**, and **400**, which tiers combine transient or impulse signals exciting simultaneously from switch array **12***a*, **12***b*, . . . , **12***p* additively, being capable of producing high amplitude picosecond pulses on planar output transmission line **500**. Each stage or tier of the combining tree matrix network may comprise a row of dual branch energy coupling networks of the type discussed in connection with FIGS. **1** and **2**, and it is to be understood that such devices have been illustrated only schematically in FIG. **3** as a matter of convenience. For example, the dual branch coupling network **103**, **103***a*, **203** of FIG. **3** corresponds to the network of FIG. **1** having arms **3**, **3***a*, and **5**, respectively. Similar dual branch network elements are represented in FIG. **3** in tier or stage **100** as respectively having arms **113**, **113***a*, **203***a*; **123**, **123***a*, **213**, **124**, **124***a*, **213***a*; and so forth. Tier **300** has two such dual branch networks, one of which networks is illustrated and has arms **303**,**303***a*, and **403**. The final combining tier **400** has a single dual branch network, of which arms **403** and **500** are shown fully and arm **403***a* in part.

It is seen with reference to the dual branch network **103**, **103***a*, **203** of tier **100** that arms **103** and **103***a* have 50 ohm impedance inputs both of which are translated to 100 ohm impedance lines adjacent their common junction with 50 ohm impedance line **203**. The remaining dual branch networks of the tree are similarly constructed in accord with the principles set forth in the discussion of FIGS. **1** and **2**, including the dual arm output combining element employing arms or branches **403**, **403***a*, **500**. While no substrate or ground plane respectively corresponding to the dielectric sheet **1** and ground plane **2** of FIG. **1** are illustrated in FIG. **3** merely as a matter of convenience, it is to be understood that stages **100**, **200**, **300**, and **400** may be bonded to such a dielectric substrate, and may be used with a similar ground plane. Furthermore, additional circuit elements such as energy collectors **10***a*, **10***b*, . . . , **10***p* and switch arrays **11***a*, **11***b*, . . . , **11***p* and **12***a*, **12***b*, . . . , **12***p* may be additionally supported by well known techniques in common upon the same dielectric substrate.

As noted previously, the elemental energy collectors **10***a*, **10***b*, . . . ,**10***p* are individually associated with corresponding elements of switch arrays **11***a*, **11***b*, . . . , **11***p* and **12***a*, **12***b*, . . . , **12***p*, the conductivity of the elements of these switching arrays being cooperatively controlled through well known mechanical or electrical means indicated by dotted lines **16** and **17** by switching synchronizer **505**.

The structure of the switch array systems in relation to collectors **10***a*, **10***b*, . . . , **10***p* and to the network input terminals of tier **100** of the tree matrix may be appreciated by considering how switching synchronizer **505** is related to the circuits leading to tier **100** from antenna collectors **10***a* and **10***b*. Collector **10***a*, for example, is connected to the blade of switch **11***a*. In the position shown in FIG. **3**, the current path from collector **10***a* is through switch **11***a* and transmission line **15***a*. The current path to input line **103** of the dual branch network **103**, **103***a*, **203** is completed through the blade of switch **12***a*.

It is observed, at any one instant of time, that switches **11***a* and **12***a* are synchronously positioned by the switching synchronizer **505** through cooperatively operated control means **16** and **17** so as to complete one of two paths between collector **10***a* and line **103**. The first transmission line path **15***a* is characterized by a nominal standard transmission delay, which may be substantially zero, while a second circuit path of different character is formed when the blades of switches **11***a* and **12***a* contact the respective terminals of transmission line **16***a*. Line **16***a* has a predetermined delay characteristic greater by a fixed amount Δ than the delay of transmission line **15***a*. It will be seen that elements **11***a*, **12***a*, **15***a*, and **16***a* cooperate as a dual state delay means. The fixed delay Δ is thus seen to be obtained by introducing lengths of non-dispersive elec-

tromagnetic delay lines, such as may be provided by high quality coaxial cable or strip transmission line, of electrical length L such that $L/c = \Delta$, where c is the velocity of propagation in the delay line medium. The time delay Δ characterizing delay devices **16***a*, **16***b*, **16***c*, . . . , **16***p* is equal to the delay Δ of the yet-to-be discussed delay device **503**, but is otherwise arbitrary in value.

Similarly, switches **11***b* and **12***b* operate as a dual state delay means and are synchronously positioned by the switching synchronizer **505** through the agency of the respective control means **16** and **17** to complete one of two current paths between collector **10***b* and input terminal of line **103***a* of the same dual branch coupler **103**, **13***a*, **203**. A first path via transmission line **15***b*, like the path through line **15***a*, is characterized by a particular nominal delay equal to the nominal delay of line **15***a*. A second circuit path is found when the blades of switches **11***b* and **12***b* contact the respective terminals of transmission line **16***b*. Line **16***b* has the same delay characteristic of transmission line **16***a;* i.e., it appears to be Δ units longer than line **15***b* or line **15***a*.

It is seen that similar alternate current paths are selected by the operation of corresponding first and second switches in an array of dual state delay devices, each under synchronous control of switching synchronizer **505**, between collector elements **10***a*, **10***b*, **10***c*, . . . , **10***p* and associated network input terminals of the arms of the respective dual branch couplers throughout the entire tier **100**. It is seen that collector elements **10***a*, **10***b*, . . . , **10***p* have, in the apparatus illustrated in FIG. **3**, equal sensitivities and equal spacing so as to form a lineal antenna array; therefore, lines **15***a*, **15***b*, . . . , **15***p* and lines **16***a*, **16***b*, . . . , **16***p* all have equal nominal delay characteristics, such as substantially zero. Also, the Δ value for each line **16***a*, **16***b*, . . . , **16***p* has a predetermined constant value. It will be clear to those skilled in the art that other combinations are feasible; for example, antenna arrays are known in the art in which the collector elements are deliberately spaced at different intervals. It will be clear that in the latter kinds of antennas, the delay Δ may vary according to the varying collector element spacing. It will be understood that switch arrays **11***a*, **11***b*, . . . , **11***p* and **12***a*, **12***b*, . . . , **12***p* may be mechanical switches operated by mechanical linkages **16** and **17**. On the other hand, elements **16** and **17** may be electrical current paths for operation under control of switching synchronizer **505** of known types of latching or other ferrite transmission line or semiconductor diode phase shifters or delay devices.

The respective outputs of switch array **12***a*, **12***b*, . . . , **12***p* are connected in pairs to the transmission line input arms of the couplers of tier **100**. Stage **100** of the electromagnetic energy propagating tree matrix comprises $p/2$ elemental couplers, each having two symmetric arms (such as the respective arms **103** and **103***a*, **113** and **113***a*, and so forth). The combined outputs of the $p/2$ elemental couplers of stage **100** respectively appear on $p/2$ output or third port, 500 ohm arms, such as ports **203** and **203***a* of the first elemental coupler of stage **200**.

Stage **200** consists of $p/4$ elemental couplers, represented in the drawing by the coupler employing symmetric arms **203** and **203***a*. These arms are seen to vary in impedance from 50 ohms at their input to 100 ohms adjacent their junction with the 50 ohm arm **303**.

The third stage **300** of the tree matrix consists of $p/8$ elemental couplers, represented in the drawing by the elemental coupler employing symmetric arms **303**, **303***a*. These arms **303** and **303***a* are also seen to vary in impedance from 50 ohms at their input to 100 ohms at their junction with the 50 ohm output port **403**.

The final stage **400** of the tree matrix consists of $p/16$ or a single elemental coupler having input arms **403** and **403***a*. These arms **403** and **403***a* also vary in impedance from 50 ohms at their input to 100 ohms at their junction with the 50 ohm output port line **500**. It is to be understood that the symmetric arms of the successive stages of the tree matrix are of length always greater than $c\tau$. It will be understood that the effective junction regions respectively attached to the junctions coupling tiers **100**, **200**, **300**, and **400** are all large compared to $c\tau$.

In the typical combining tree matrix illustrated in FIG. **3**, a quadruple tier matrix has been illustrated. It should be understood that other numbers of tiers, with the possibility of consequent multiplication of the output signal on line **500**, may readily be employed. The voltage amplification for increased numbers of tiers is readily calculated from equation (7). Thus, a unit voltage signal into two associated input ports produces $\sqrt{2}$ volts across a load at an output port. In a double tier system, a unit voltage input produces 2 volts at the output. The triple tier arrangement produces $2\sqrt{2}$ volts. A quadruple tier system with 16 unit voltage generators at 16 inputs yields 4 volts on the single output line **500**. Characteristic of each such matrix and independent of the number of tiers or stages in the matrix is the fact that the distances or propagation times from each first tier coupler input terminal to the output of the last stage or tier is always equal.

Understanding of the invention will be aided by consideration of the operation of the FIG. **3** structure so far discussed, but with reference to FIG. **4**. When each of the antenna array collector elements is illuminated by a transient or impulse type of carrier wave of electromagnetic energy, that wave will have a front making an arbitrary angle θ with respect to an imaginary line drawn through collectors **10***a*, **10***b*, . . . , **10***p* of FIG. **3**. If each such collector is illuminated equally by such a wave front then, for some predetermined value θ_A of the angle of incidence θ, all of the signals passing, for example, through transmission line paths **15***a*, **15***b*, . . . , **15***p* will add coherently at the output transmission line or port **500**, as in FIG. **4***a*. These signals will emerge at port **500** to form a short pulse of duration τ seconds. Coherent signals simultaneously injected, for example, into arms **103**, **103***a*, at points equidistant from line **203** combine so that the total voltage contribution V_T from arms **103** and **103***a* goes into arm **203** and no signals are reflected from the junction into arms **103** or **103***a*. Every other such coupler junction has the same property. Each such junction is one hundred per cent efficient when signals from adjacent paired energy collectors flow simultaneously into corresponding arms such as arms **103**, **103***a*. It is seen that the total tree matrix has the same property, being made up of like dual branch couplers; thus signals arriving at angle θ_A are added coherently on transmission line **500**, as in FIG. **4***a*.

For other values θ_o of the angle of incidence θ, the individual signals received by the respective corresponding collectors **10***a*, **10***b*, . . . , **10***p* may arrive at port **500** separated in time, as in FIG. **4***b*. The larger the value of *p* (the total number of collector elements **10***a*, **10***b*, . . . **10***p*), the greater the ratio between the maximum signal obtained at port **500** for the peak axis at angle θ_A of an antenna receptivity pattern of finite width and the off-axis contributions to the array of energy collectors. When the angle of incidence θ_o deviates only slightly from the antenna pattern peak sensitivity direction θ_A, the peak amplitude of the combined signal seen at port **500** drops and the signal energy spreads in the time domain as seen in FIG. **4***c*. FIGS. **4***a*, **4***b*, and **4***c* may be further understood by observing that the antenna pattern width in space may be defined in terms of them. For example, when the amplitude of the signal at port **500** drops to half of its peak value at θ_A, the antenna receptivity pattern width may be defined or measured in terms of the time interval at the ¼ voltage points of the curve of FIG. **4***c*.

It will be understood that the angle θ_A of the peak of the antenna pattern may be steered by mechanical steering of the antenna of FIG. **3**. Alternatively, electronic steering of the receptivity pattern and consequently of θ_A may be achieved in the usual manner by adding electronically variable delay devices or phase shifters for the purpose in each of the lines leading from each of the antenna collector elements **10***a*, **10***b*, . . . , **10***p*.

Signals output at port **500** of the tree matrix final stage **400** are supplied through a switching mechanism including switches **501**, **504** to utilization apparatus **510**. The blades of switches **501** and **504** are caused to operate synchronously with the respective corresponding blades of switch arrays **11***a*, *11b*, . . . , **11***p* and **12***a*, **12***b*, . . . , **12***p*. Synchronous operation is again brought about by mechanical or electrical control means **506**, **506***b* under operation of control **506***a* by the switching synchronizer **505**. Port **500** is alternately connected through a transmission line **503** having a delay Δ greater than line **502**, and then through line **502**. Elements **501**, **502**, **503**, and **504** together form an output dual state delay means. In what will be called the mode A situation, the delay Δ is removed from the transmission lines leading signals from collectors **10***a*, **10***b*, . . . , **10***p* to the respective inputs of tier **100** of the tree matrix. However, in the mode A situation, the delay Δ is inserted by switches **501** and **504** between port **500** and utilization apparatus **510**.

Conversely, in what may be called mode B operation, a delay Δ is inserted in each of the transmission lines leading from collectors **10***a*, **10***b*, . . . , **10***p* to the respective input terminals of tier **100**. In mode B operation, the delay Δ is removed by switches **501** and **504** between port **500** and utilization apparatus **510**.

As noted previously, when the angle of incidence θ is θ_A, all signals arrive from collectors **10***a*, **10***b*, . . . , **10***p* simultaneously and coherently add at port **500**. For any other angle of incidence θ_o, the response at port **500** in the mode A situation is a train of pulses as in FIG. **4***b*. Such a statement is fully accurate, however, only when the driving point impedances of the antenna collector elements **10***a*, **10***b*, . . . , **10***p* are individually substantially equal to the impedances of the respective associated transmission lines **15***a*, **15***b*, . . . **15***p* over a sufficiently extended frequency domain. Such a perfect impedance match is difficult and costly to attain. However, the consequence of relaxing matching tolerances is that a portion of the energy in impulses passing each dual branch coupler junction is reflected back toward the collector elements **10***a*, **10***b*, . . . , **10***p*. Similarly, reflected waves entering a given junction region from below continue to see no discontinuity until an antenna collector element is reached. At the antenna collector locations, both types of waves are rereflected, causing the responses to spread and generating a very large number of pulses at various time locations in the output port **500**.

To obviate this difficulty, the previously described apparatus is used in a manner making use of the inherent properties of the signals involved so that the effects of undesired signals are substantially eliminated. For this purpose, the apparatus is set to operate in mode B, delay elements **16***a*, **16***b*, . . . , **16***p* of Δ seconds retardation being injected in series in the current paths from each respective antenna collector element **10***a*, **10***b*, . . . , **10***p*. The presence of delay elements **16***a*, **16***b*, . . . , **16***p* delays each signal flowing from each collector **10***a*, **10***b*, . . . , **10***p* toward port **500** by Δ seconds. However, signals re-reflected by antenna collectors **10***a*, **10***b*, . . . , **10***p* after internal reflection in any tier of the matrix network are delayed by 2Δ, 4Δ, 6Δ, . . . , or *s*Δ sections, where *s* is an even integer.

Referring to FIG. **5**, FIG. **5***a* illustrates an idealized pattern which might appear on a conventional cathode ray radar or other oscilloscope or which might otherwise represent the time sequence of the input to utilization device **510** with the apparatus receiving an impulse from space while operating in mode A. A signal **600**A of K volts amplitude and Δ time delay corresponding to a signal received by the antenna at time zero is accompanied by a false representation pulse **601**A caused by undesired reflections within the system of FIG. **3**.

FIG. **5***b* represents a related idealized time pattern showing the input to utilization apparatus **510** with the apparatus receiving an impulse from space while operating in the mode B condition. A desired signal **600**B again of K volts amplitude and delay Δ seconds again corresponding to a signal received from space by the antenna at time zero is present. Also present is a false representation **601**B caused also by undesired reflections within the system of FIG. **3**, but shifted in time so as to appear Δ seconds later than the spurious mode A pulse **601**A of FIG. **5***a*.

Multiplication of the signals shown in FIGS. **5***a* and **5***b*, using the same zero time reference, yields the enhanced signal **602** of FIG. **5***c* having an amplitude of K^2 volts and the same Δ seconds time delay with reference to zero time. Spurious signals **601**A and **601**B are greatly reduced in magnitude and may approach zero level in FIG. **5***c* if the background noise level is sufficiently low.

In essence, the invention provides means for receiving impulse signals from space by an array of cooperating sensors, such as have commonly been exploited in radar or in direction finding, and for processing and combining such signals by means permitting significant enhancement of received impulse signals genuinely representing useful data and also providing significant

degradation of spurious responses. A situation met with typically in radar, direction finding, and the like systems involves undesirable responses of an antenna array and signal combining network for a signal arriving off the boresight axis θ_A; that is, in a direction other than the direction of the axis of symmetry of the antenna receptivity pattern. The response typically consists of a primary response plus various anomalous responses which arise internally of the signal combining system mainly because of mismatches at network junctions in the combining system.

It will be apparent from the foregoing that such spurious responses are substantially, if not entirely, eliminated by the mechanism of the present invention. To accomplish the desired effect, the invention is successively and alternately operated in two particular modes. Switches are operated in a mode A in such a way as to introduce a delay Δ in the output of the combining network. Switches are again operated, translating the system into mode B operation. Here, the delay Δ is removed from the output of the combining network and is injected instead in series with each antenna collector element. The time of arrival of the primary response impulse at utilization device **510** is unchanged in shifting cyclically from mode A to mode B operation. However, anomalous returns are delayed by Δ seconds in the B mode with respect to their timing in mode A. It is seen that simple multiplication of pairs of successive inputs to utilization device **510** yields the desired effect of enhancement of desired signals and degradation of undesired signals.

It is obvious to one skilled in the art that multiplication of successive A and B mode signals is readily achieved by well known means. A variety of known approaches may be exploited and it is therefore considered to be unnecessary to describe here examples of such mechanizations in any detail.

However, it should be clear that the utilization apparatus **510** of FIG. **3** may comprise simply two type A indicator storage tubes. For example, one or more mode A samples looking like FIG. *5a* may be stored on a first cathode ray storage tube screen. The apparatus then may be switched to mode B operation and signals like that of FIG. *5b* stored on the second storage tube screen. Multiplication may be accomplished mentally, or after suitable measurements are taken, and a graph like FIG. *5c* constructed.

Simple analog means are well known for the substantially instant multiplication of pulse signal amplitudes. Such make it readily possible, for example, to operate the invention in the A and B modes, delaying the A mode response by a conventional delay line-amplifier circuit by the fixed frame time of operation on the A mode, and then applying the delayed A mode response and the delayed B mode response in proper synchronism to the inputs of a multiplier whose output is passed for observation on a type A radar screen. Cyclic operation of such a system is evidently feasible.

More sophisticated mechanizations are readily possible using apparatus well known in the prior art. By sequentially operating the antenna array and processing system in modes A and B, and by digitally storing successive respective output wave forms, quantized versions of the received signals for the two modes may readily be stored in individual locations in a general purpose digital processor memory. For example, digital versions of the mode A and mode B wave forms may be cyclically stored in individual memory register circuits. The data is synchronously shifted out of the registers at the appropriate instant of time and an ordinary digital multiplication follows. If the computed result is desired in analog form, it is evident that appropriate conventional digital-to-analog conversion may be employed to construct an image such as that of FIG. *5c* for presentation on the screen of a cathode ray tube.

FIG. **6** represents, by way of example, a general method and apparatus for performing the functions of the utilization apparatus **510** of FIG. **3** by employment of digital processing techniques. In FIG. **6**, it is shown that the invention may be practiced by the cooperative employment of certain circuits often present in conventional sampling high frequency oscilloscopes and of certain of the circuit elements conventionally found in simple general purpose digital computers.

Referring particularly to the part **700** of the FIG. **6** apparatus for performing the sampling oscilloscope functions, it will be seen that apparatus **700** lends itself to sampling wide band width signals by use of a stroboscopic method by means of which an input wave form may be reconstructed from samples repetitively taken during a number of successive recurrences of an input wave form. An input wave having a given repetitive frequency is continuously sampled at a slightly lesser repetition frequency, and the sampled voltages are stored. In the instance that the sampling system is to provide a display, the sampled wave form voltage is measured and is used to position the electron beam of a cathode ray tube. The sample taken during the next succeeding sampling event is derived at a slightly later point on the input wave form. The cathode ray is moved incrementally in a horizontal sense, but is repositioned vertically according to the magnitude of the newly sampled voyage. Accordingly, there is plotted on the face of the storage cathode ray display, in point by point fashion, the reconstructed wave form by using as many, for example, as 100 successive samples to reconstruct the input wave form. In the present invention, the sampled voltages are supplied by the sampling system **700** for processing in a conventional digital computer system **721**.

Referring particularly to the sampling system **700** of FIG. **6**, the wave form from switch **504** of FIG. **3**, which may, in mode A operation, for example, consist of pulses corresponding to the idealized pulses **600A** and **601A** of FIG. *5a*, is applied as an input to the sampling system **700**. As is suggested above, no actual display of the signals in sampling apparatus **700** is required for use in the present invention, although such may be convenient.

The sampling system **700** includes a sampling gate **701** and a sample and hold circuit **703** which together comprise what is known in the art as a sampling head **704**. Sampling apparatus **700** also includes a time base generator **702** and a sample amplifier **705**, and may include an oscilloscope display **706**. The input wave form to sampling head **704** comprises, in the system A mode, for example, signal wave **600A** and **601A**, supplied directly to sampling gate **701** which is enabled by a signal provided by the time base generator **702**. The

output from sampling gate **701** is coupled to the input of sample and hold circuit **703**, which circuit is also triggered by a signal supplied by time base generator **702**. The sample and hold circuit **703** supplies signals corresponding to input signal **600A** and **601A**, when the apparatus is in the A mode, to the sample amplifier **705**. The latter amplifier **705** provides output signals for application after conversion to analog-to-digital converter **720** directly to digital processor **721**, as will be explained.

Should it be desired that a presentation of the output of sample amplifier **705** be provided, the latter also provides a signal to the vertical deflection circuits of oscilloscope display **706**. The horizontal sweep signal applied to the horizontal deflection circuit of display indicator **708** is supplied via lead **702***a*. Time base generator **702**, which supplies the horizontal sweep signal via lead **702***a*, also provides unblanking signals to a conventional electron beam intensifier circuit associated with display indicator **708**. Erasure signals are supplied in the usual manner.

Time base generator **702** is a conventional circuit for application in sampling oscilloscopes and elsewhere. It generates a sampling wave form illustrated by the timing wave form A of FIG. **7**, which is held, for instance, in synchronism with the repetition cycle of the input signal **600A** by means of synchronizer signals from terminal **505A** being applied to generator **702**. The sampling wave form A of FIG. **7** provides a time base synchronized with respect to the input signal comprising elements **600A** and **601A**, and is used in a conventional manner in time base generator **702** to provide triggering wave forms for sample gate **701** and for the sample and hold circuit **703**.

As previously indicated, time base generator **702** generates the sawtooth sweep wave that is shown at A in FIG. **7**. These repetitive signals are synchronized in a conventional manner to the cycles of the repetitive input wave from switch **504** by means of the synchronizer input to generator **702**. The wave A therefore provides a time base voltage for the system **700** with respect to input waves such as wave **700A** and **601A** when the system is operating in the A mode. Time base generator **702** also provides in a conventional manner a slowly increasing ramp voltage B which includes many cycles of wave A. The slowly increasing ramp voltage B is combined in a conventional manner within time base generator **702** with wave A for the purpose of generating for use in sampling head **704** a trigger pulse whenever wave A intersects the slowly increasing ramp B level. The trigger pulses thus generated are used within the sampling head **704** to trigger sampling gate **701** and sample and hold circuit **703**. Accordingly, upon each occurrence of the trigger pulse, the sampling gate **701** transmits a voltage sample of the input wave from switch **504** to the sample and hold circuit **703**, wherein the sample is stored until the next occurring sample is obtained. Wave form A, being synchronized to the input wave from switch **504**, cooperates with the slowly increasing ramp voltage B so that the samples obtained by sample gate **701** slowly progress across the repetitive input wave form. That is, a quantized output wave **705A** is generated, which is a quantized version of the received wave obtained from switch terminal **504**, for application to analog-to-digital converter **720**. A corresponding wave **705B** may be formed by processing waves **600B** and **601B**. If desired, the wave forms **705A** or **705B** may be presented on the screen of the cathode ray tube **708** of display **706**. For this purpose, the samples held in sample and hold circuit **703** may also be supplied via sample amplifier **705** to the vertical deflection circuit of indicator **706**. The slowly increasing ramp B voltages generated within time base generator **702** are used as horizontal deflection signals in display indicator **708**. A version of the trigger pulses provided by time base generator **702** to enable sampling head **704** is applied to a control grid of the cathode ray tube **708** for providing unblanking signals for the electron beam. Thus, successively occurring samples obtained across the input wave such as waves **600A**, **601A** or **600B**, **601B** may be displayed on the screen of cathode ray tube **708**.

The immediately foregoing paragraphs describe the structure and operation of a conventional system for sampling repetitive wave forms and for reconstructing quantized versions of those signals for digital processing or for other purposes such as display on a cathode ray tube oscilloscope. Such systems are known in the art, though improved sampling systems may be preferred, such as that disclosed by Alexander M. Nicolson in the U.S. Pat. application, Ser. No. 844,021, filed July 23, 1969, entitled: "Method and Means for Compensating Amplitude and Time Drifts in Sampled Waveform Systems," issued June 8, 1971 as U.S. Pat. No. 3,584,309 and also assigned to the Sperry Rand Corporation.

For the purpose of processing the successive wave forms **705A** and **705B** derived within the sampling apparatus **700**, elements of a conventional general purpose digital computer **721** along with digital converters **720** and **725** may be employed. As seen in FIG. **6**, computer **721** may contain a programmer memory **722** under control of signals from terminal **505A** generated within the switching synchronizer **505** of FIG. **3**. It will be apparent to those skilled in the art that computer **721** may be synchronized by signals derived in switch synchronizer **505**. Alternatively, it may be preferred that operation of the entire system be synchronized in the conventional manner from the programmer memory **722** located within computer **721**. In any event, programmer memory **722** is a device having suitable storage elements for storing in a manner well known to those skilled in the art a program for programming further operations upon signals **705A** and **705B**.

Digital computer **721** additionally contains a second storage means which may take the form of first and second respective registers **723***a* and **723***b*, also under the control of timing signals from programmer memory **722**. Outputs from analog-to-digital converter **720**, which receives signals **705A** and **705B**, are additionally respectively applied to registers **723***a* and **723***b*. A further element of the digital computer **721** is the digital multiplier **724**. Multiplier **724** accepts the output of registers **723***a* and **723***b* when the contents of these registers are shifted upon the occurrence of a command signal from programmer memory **722**. The product output of multiplier **724** is then supplied by computer **721**, still in digital word form, to the digital-to-analog converter **725**. The latter yields, after mul-

tiplication within the computer **721** of signals **705A** and **705B**, a signal devoid of reflections, as ideally illustrated in FIG. **5***c*. The output signal **750** of converter **725** is supplied, under the control of programmer memory **722**, to utilization apparatus **726**. Utilization device **726** may comprise, for example, a cathode ray indicator **727**.

In operation, it is seen that a series of successive applications of the FIG. **5***a* signals **600A** and **601A** to apparatus **700**, followed by a substantially equal number of applications of signals **600B** and **601B** of FIG. **5***b*, yields sets of signals such as signal **705A** and **705B** for conversion into digital words by converter **720** and for storage in registers **723***a* and **723***b*. When the appropriate number of storage locations in register **723***a* is filled, programmer memory **722** causes converter **720**, by an elementary switching process, to fill register **723***b* with digital words corresponding to signals **600B** and **601B** of FIG. **5***b*. Converter **720** and registers **723***a* and **723***b* perform their functions in a conventional manner and may be controlled in a conventional manner by programmer memory **722**, as may be multiplier **724**, converter **725**, and display **726**.

When register **723***a* is filled with digital binary words, for example, corresponding to mode A signals **600A** and **601A**, and when register **723***b* if filled with data corresponding to the mode B signals **600B** and **601B**, the programmer memory **722** then, in a conventional manner, causes the data in registers **723***a* and **723***b* to shift into multiplier **724**. In the latter arithmetic circuit, the stored digital words are multiplied in the conventional manner to yield binary digital signals representing the product of signals received in the mode A and in the mode B conditions of the system. The output of multiplier **724**, being a digital signal, may be supplied to the input of a digital processing system such as a digital servo mechanism or to other apparatus accepting digital input signals. As shown in FIG. **6**, the digital product may be converted into an analog signal by converter **725** for display as signal **750** devoid of all undesired reflections or for use in other analog utilization apparatus.

While the invention has been described in its preferred embodiment, it is to be understood that the words that have been used are words of description rather than limitation and that changes within the purview of the appended claims may be made without departing from the true scope and spirit of the invention in its broader aspects.

We claim:

1. An electromagnetic signal processing system comprising:
- electromagnetic energy signal propagating, branching tree network means,
- network input terminal means,
- network output terminal means,
- first dual state delay means adapted to receive electro-magnetic signals, coupled to said network input terminal means,
- second dual state delay means coupled to said network output terminal means,
- synchronizer means for switching said first and second delay means between first and second states while maintaining the state of said first delay means opposite to the state of said second delay means, and
- utilization means for receiving the output of said second delay means.

2. Apparatus as described in claim **1** wherein said input terminal means comprises plural terminals.

3. Apparatus as described in claim **2** wherein said output terminal means comprises a single terminal.

4. Apparatus as described in claim **3** wherein said network input and output terminal means and said branching tree network means are so constructed and arranged that the energy propagation path from any one of said plural terminals to said single terminal has the same length as the energy propagation path from any other of said plural terminals to said single terminal.

5. Apparatus as described in claim **4** wherein said utilization means comprises cathode ray storage indicator means for individual presentation of signals traversing said signal processing system in said first and second states for visual simultaneous comparison thereof on a time scale basis.

6. Apparatus as described in claim **4** wherein said utilization means comprises:
- signal multiplier means having first and second inputs and outputs,
- fixed delay means,
- means operable in said first state for connecting the output of said signal processing means through said fixed delay means to said first multiplier input,
- means operable in said second stable state for connecting the output of said signal processing means directly to said second multiplier input, and
- indicator means for displaying the output of said signal multiplier.

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