United States Patent [19]

Gerst et al.

[11] **3,731,217**

[45] **May 1, 1973**

[54] **QUASI-OPTICAL SIGNAL PROCESSING UTILIZING HYBRID MATRICES**

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[73] Assignee: **Research Corporation**, New York, N.Y.

[22] Filed: **Apr. 3, 1970**

[21] Appl. No.: **25,523**

Related U.S. Application Data

[63] Continuation of Ser. No. 570,232, Aug. 4, 1966, abandoned.

[52] **U.S. Cl.** ....**330/56,** 325/446, 330/124 R, 333/11, 340/166

[51] **Int. Cl.** **H03f 3/60,** H01p 5/12

[58] **Field of Search** 330/124, 56; 307/241, 242; 333/11; 328/96, 152; 325/445, 446; 343/854; 340/172.5, 166; 332/11

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Primary Examiner—Alfred L. Brody
Attorney—Yuter & Fields

[57] **ABSTRACT**

A microwave signal processing device comprises a first phase-transform matrix having a plurality of input ports and a plurality of output ports. Signals in a first domain applied to the input ports are power divided and phase coded upon transmission to the output ports. These signals at the output ports which have been transformed into a power distributed phase-coded domain are applied to the input ports of an operator matrix which changes the characteristics of the signals. The signals at the output ports of the operator matrix are applied to the input ports of a second phase-transform matrix which retransforms the signals to the first domain and transmits the retransformed signals from its output ports.

17 Claims, 25 Drawing Figures

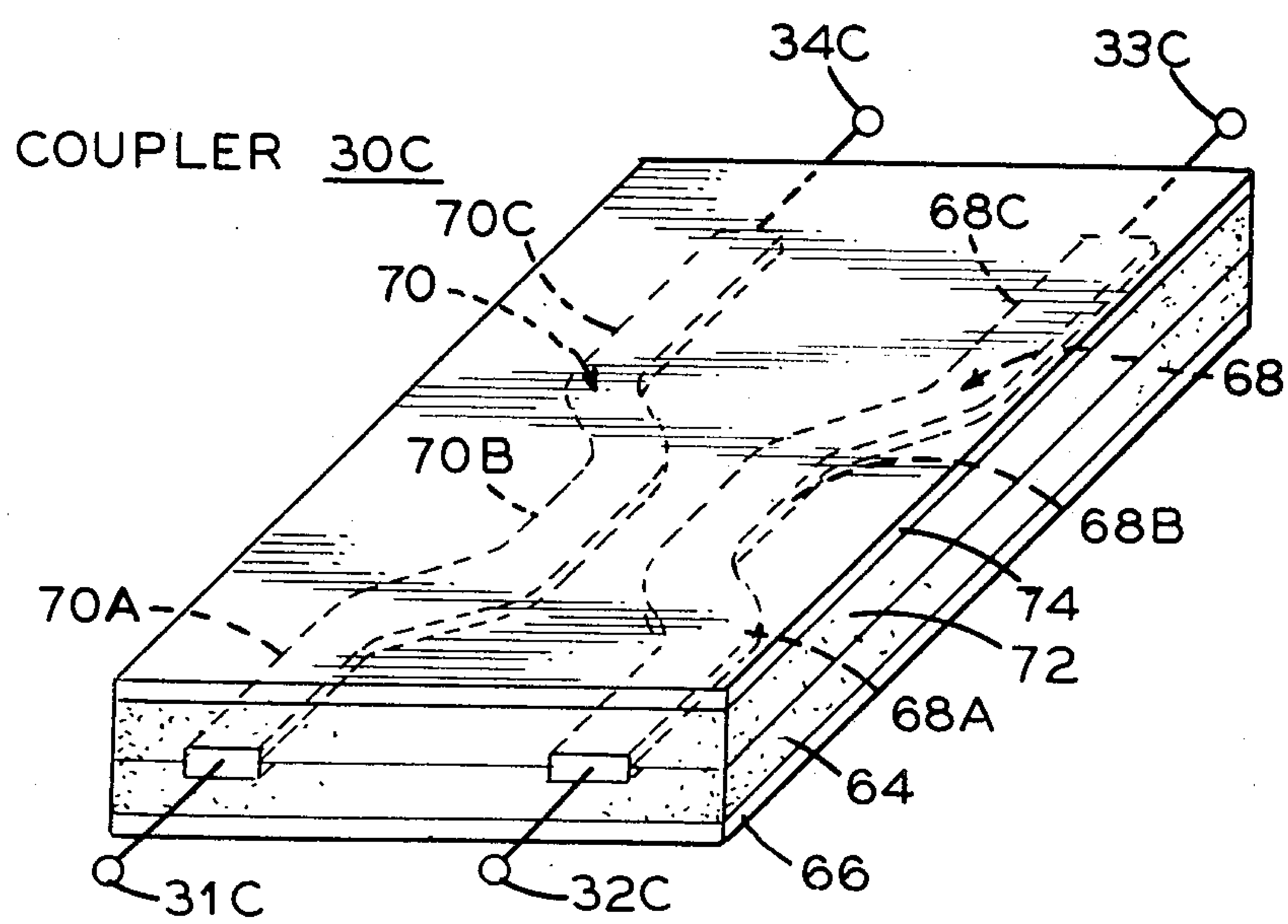

FIG. 7

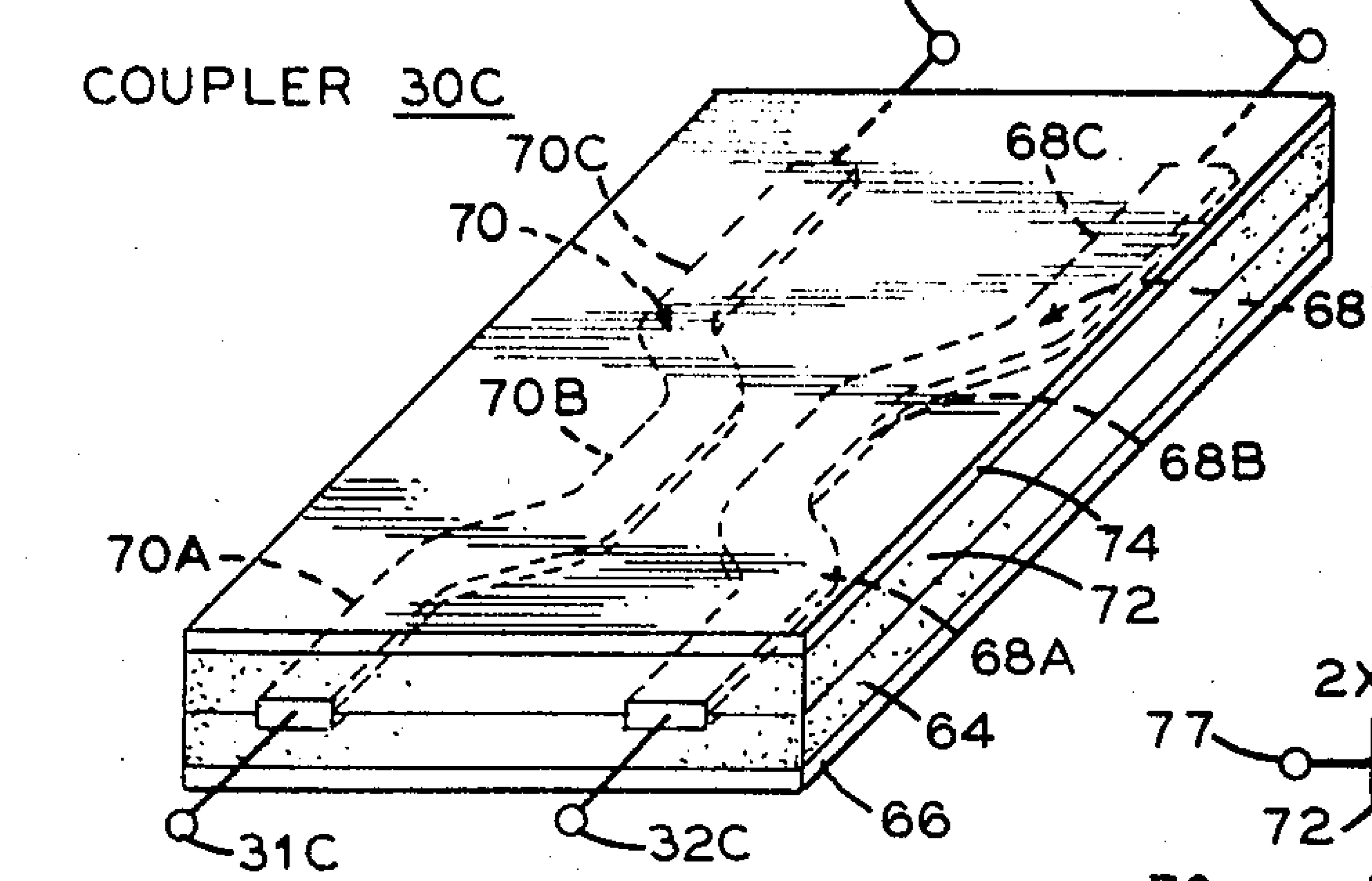

FIG. 1

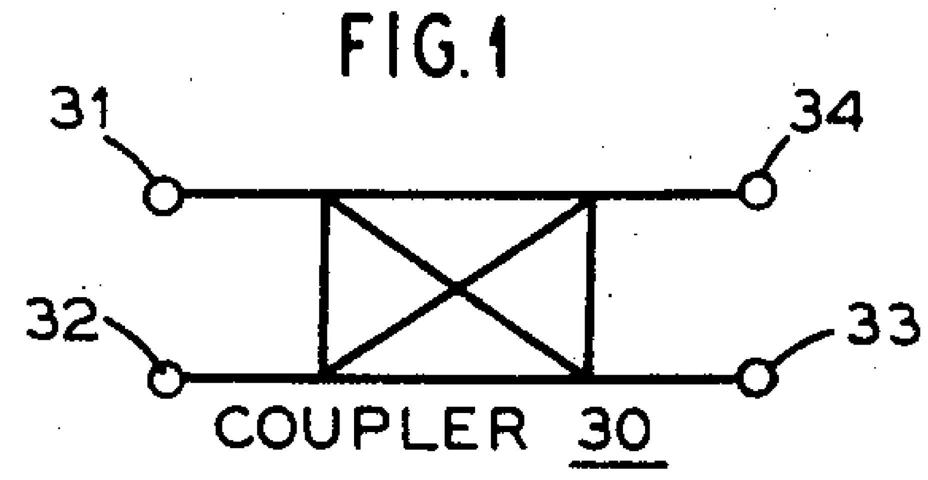

FIG. 8

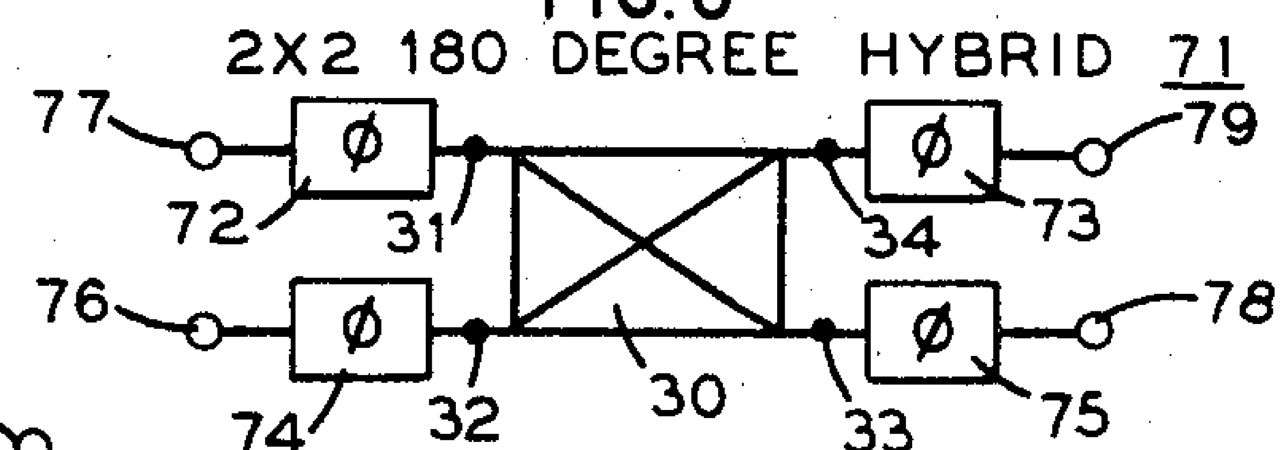

FIG. 2

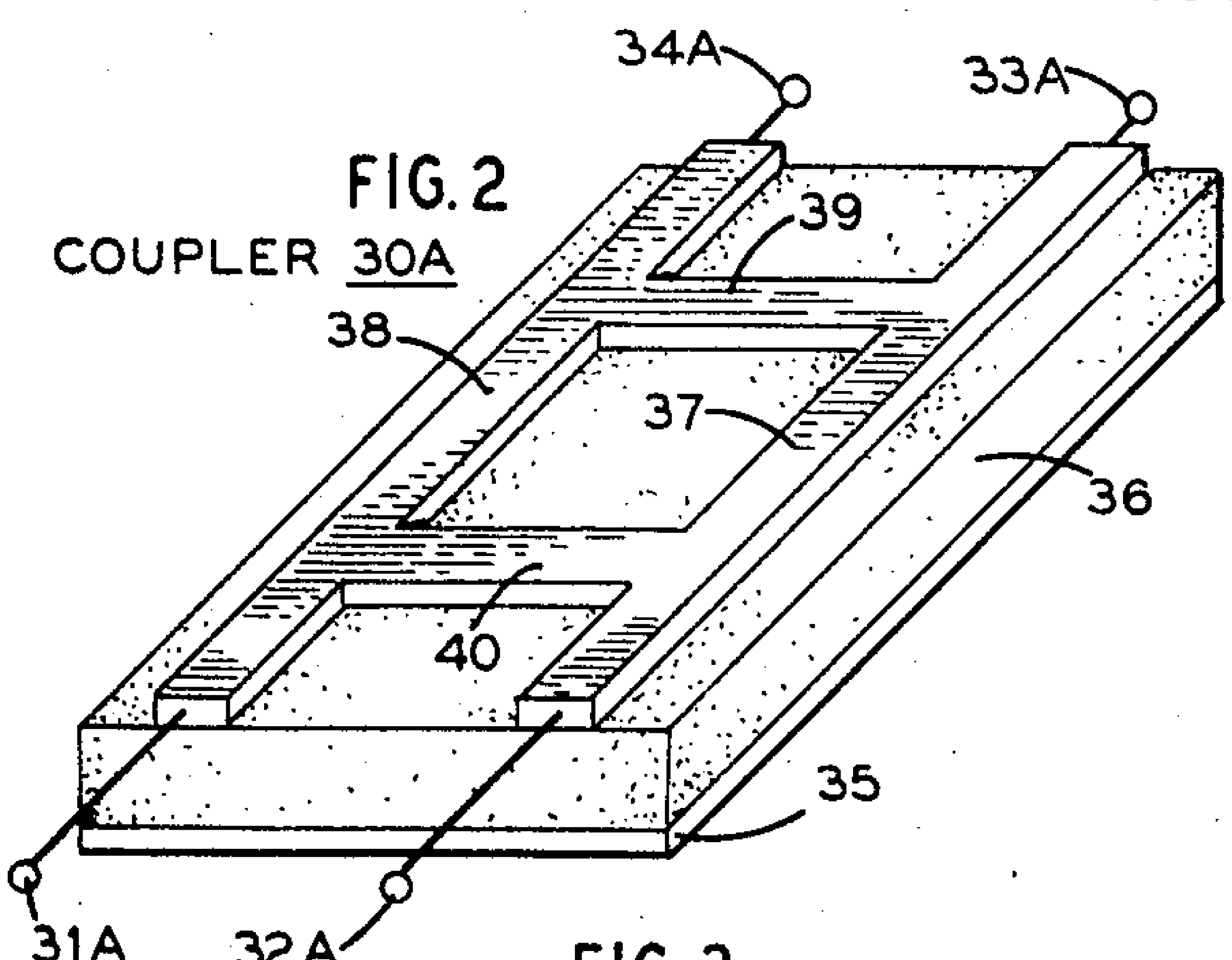

FIG. 9

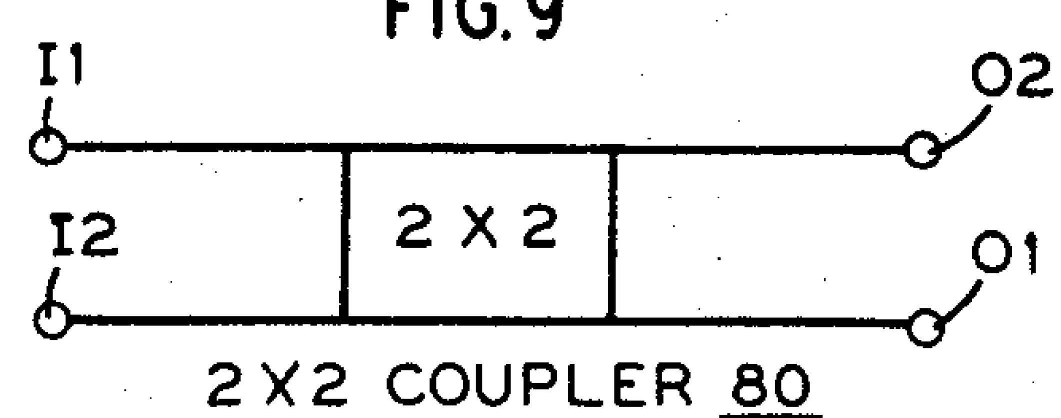

FIG. 3

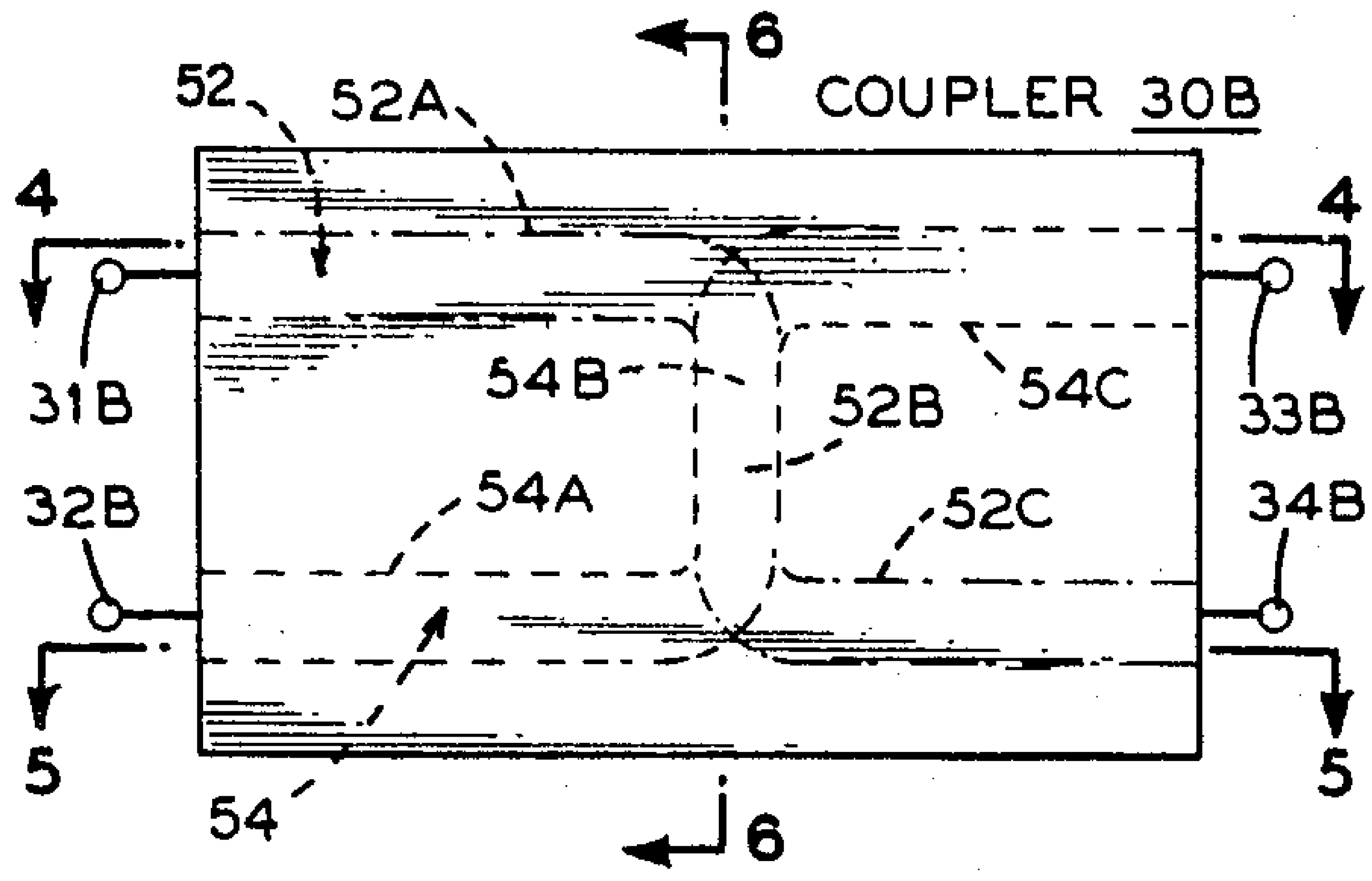

FIG. 6

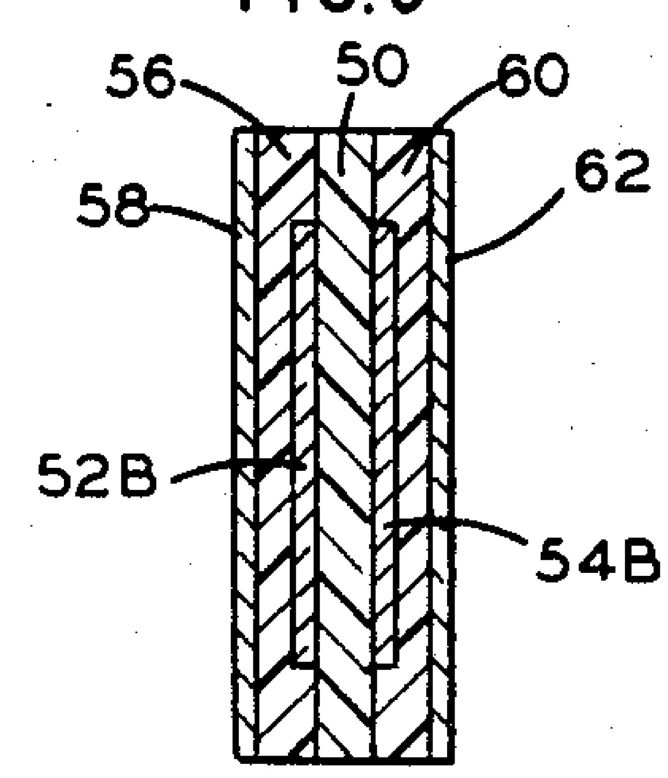

FIG. 4

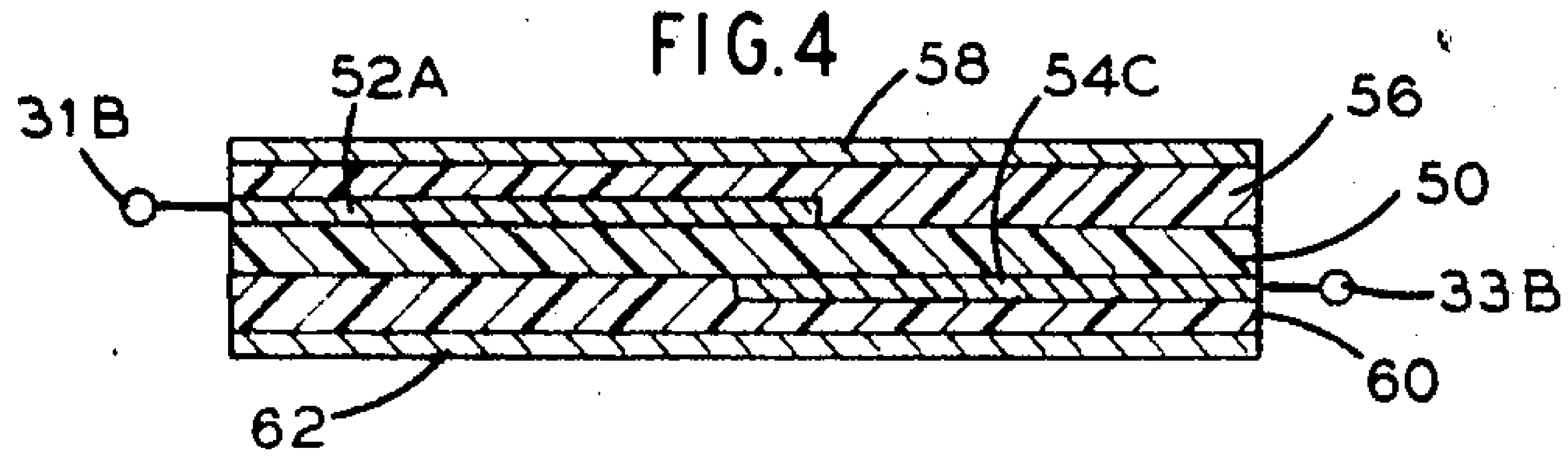

FIG. 5

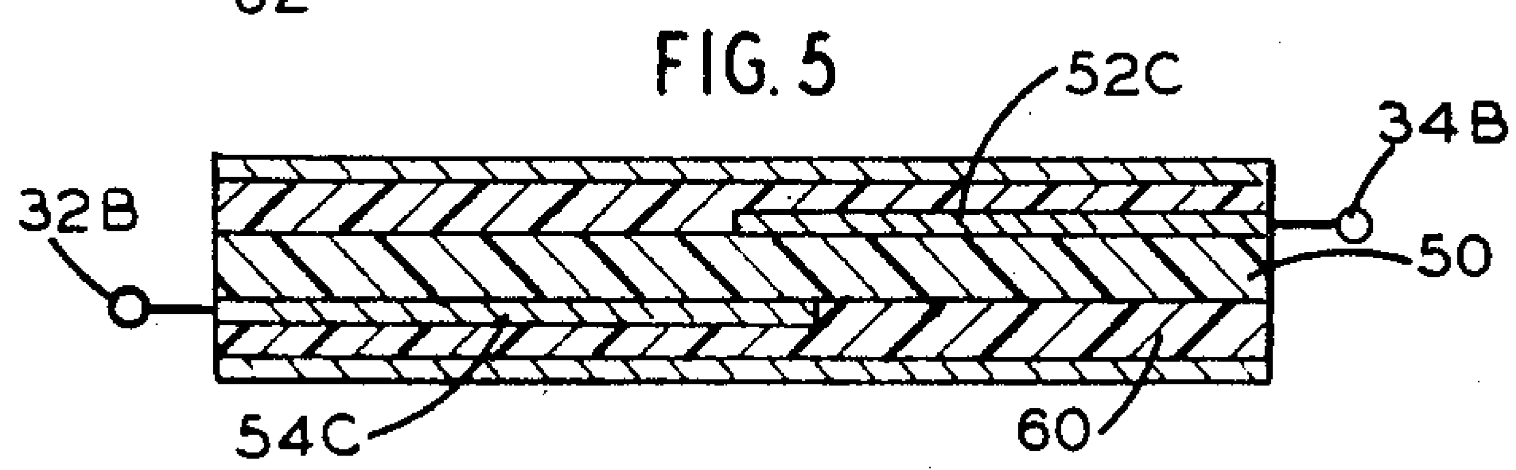

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FIG.12
4X4 MATRIX 90

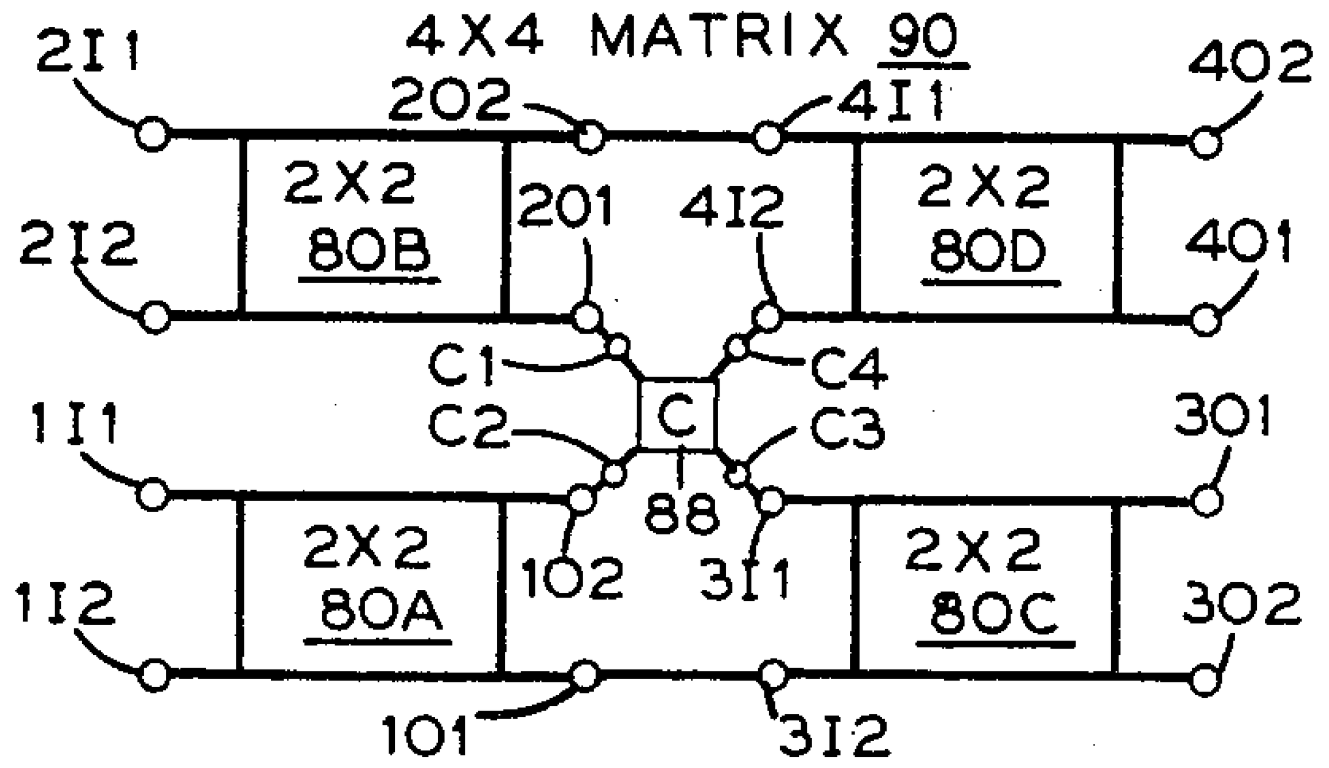


FIG.13
4X4 BUTLER MATRIX 92

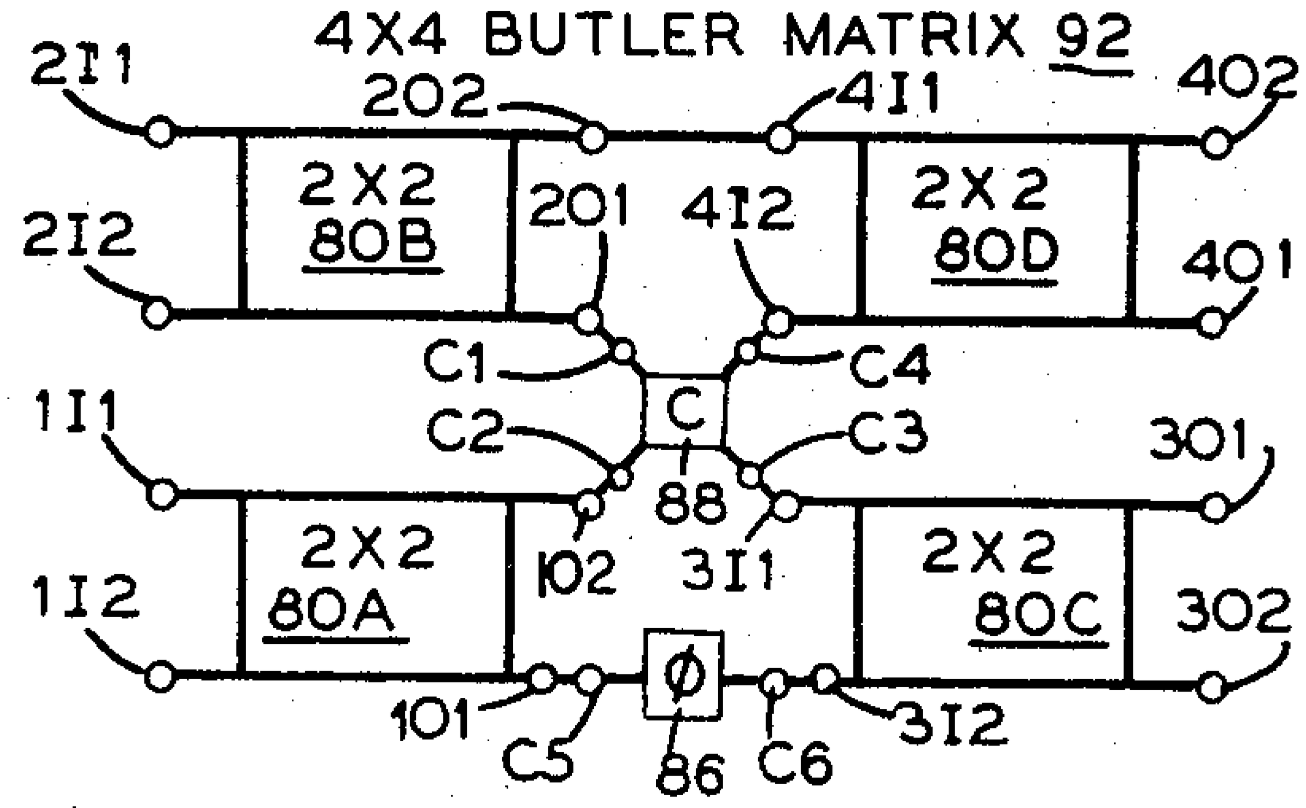


FIG.14

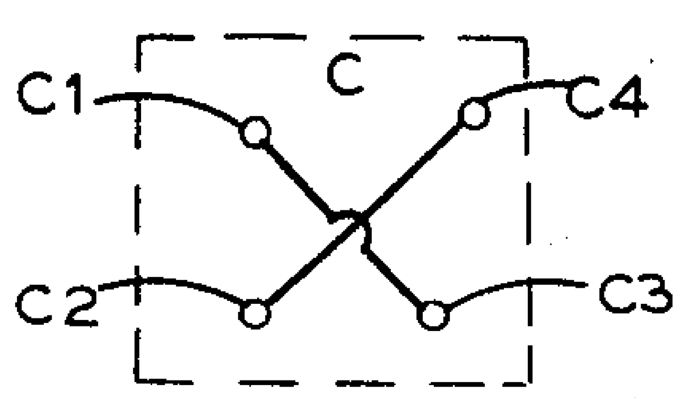


FIG. 10
CROSSOVER MATRIX 82

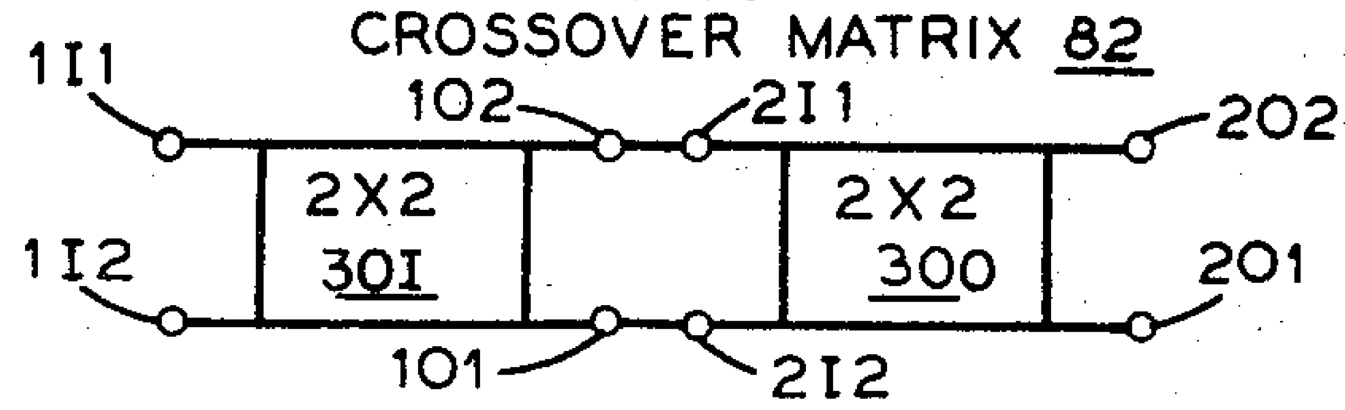


FIG.15
4X4 MATRIX 91

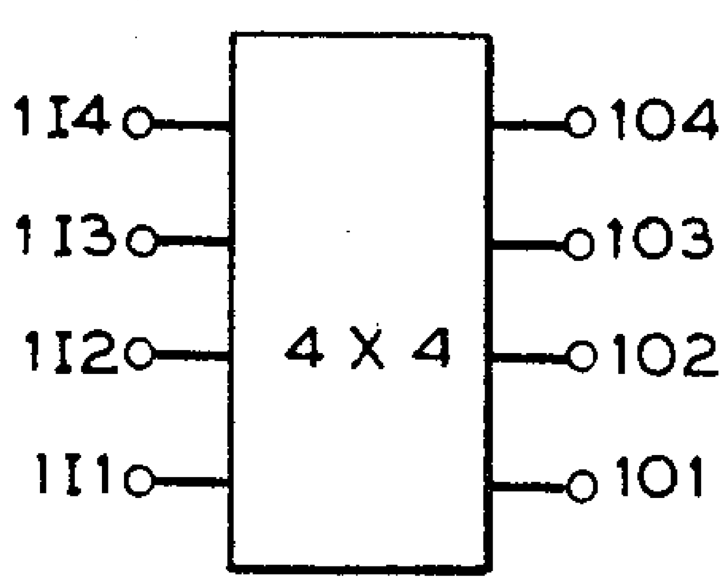


FIG.16
8X8 MATRIX 94

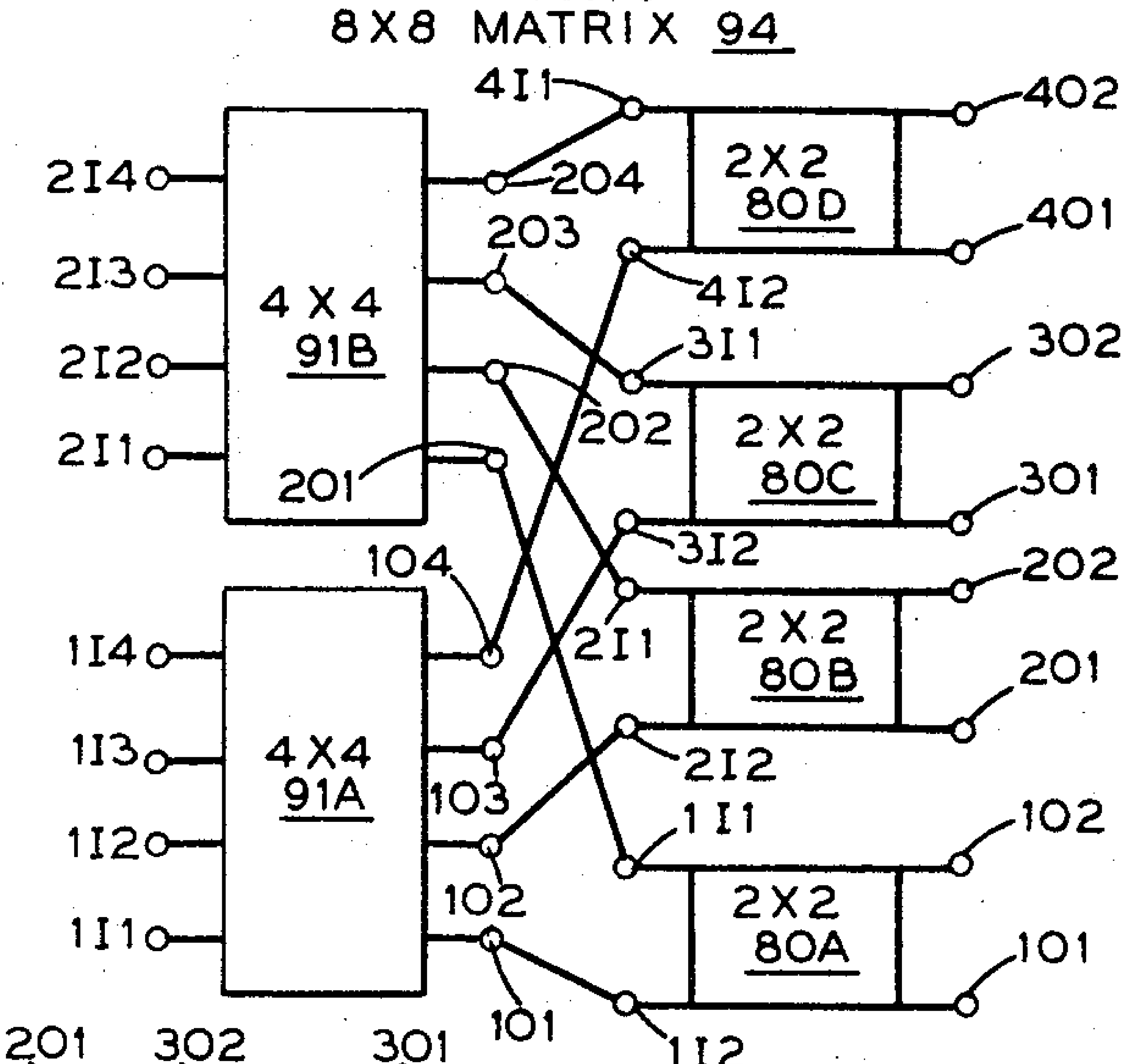
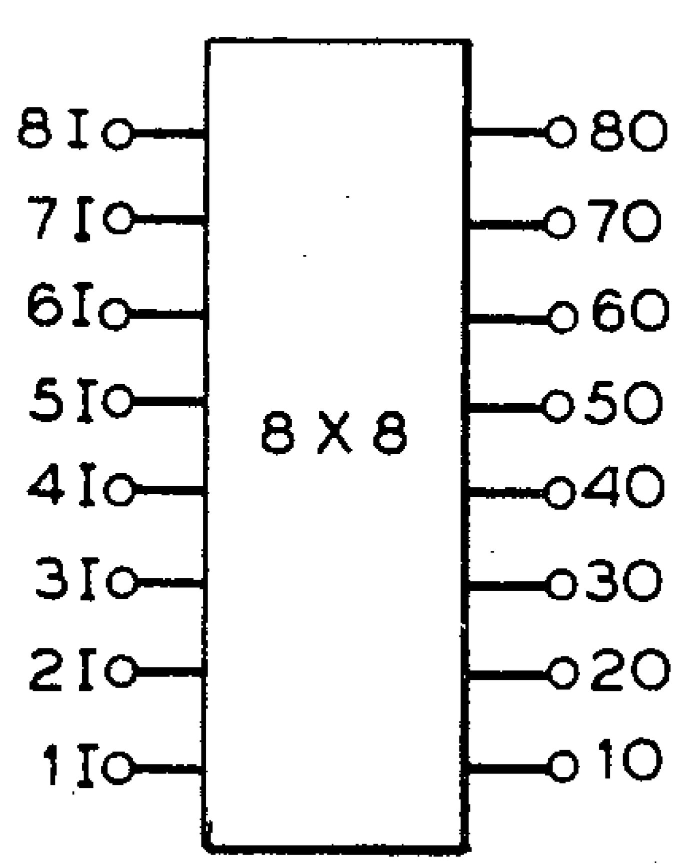


FIG.17
8X8 MATRIX 94



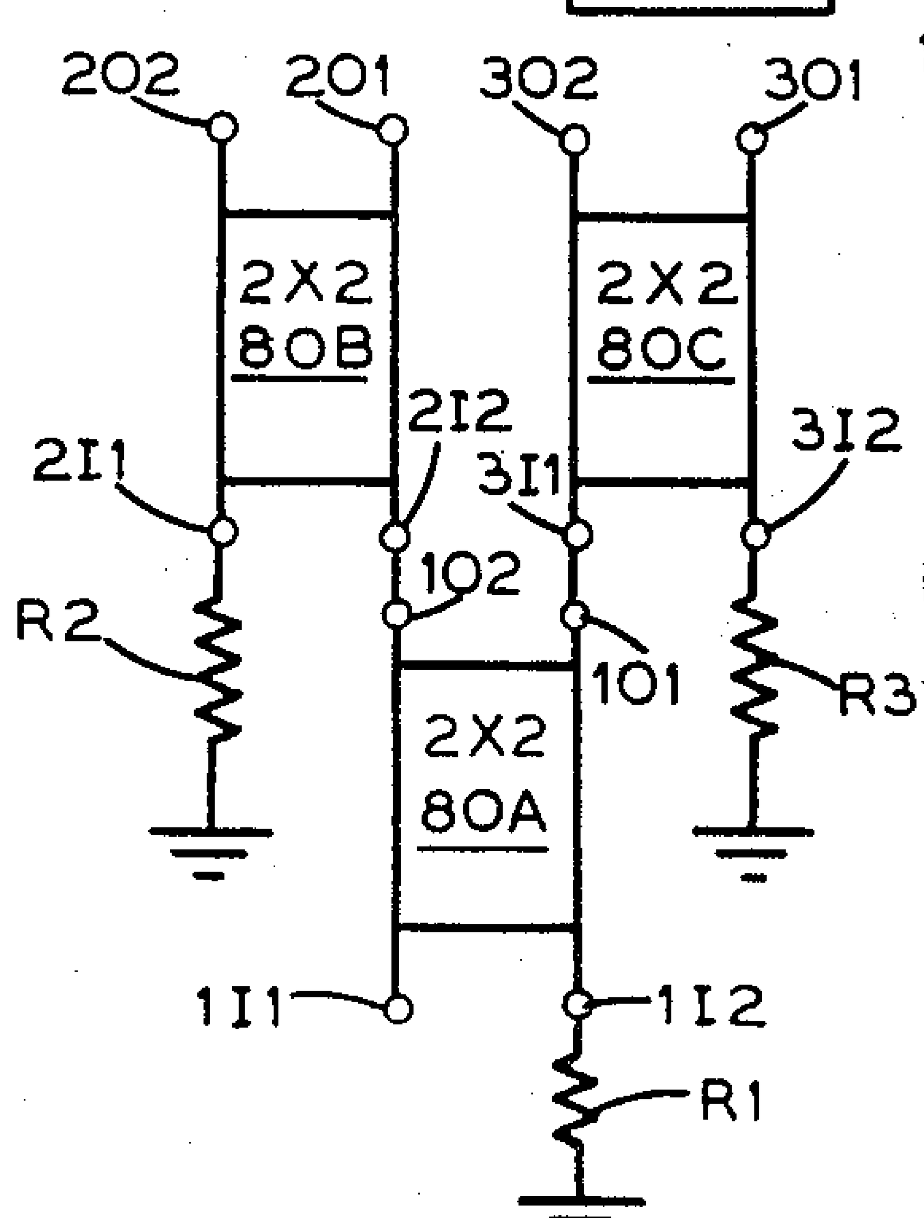


FIG.11
POWER SPLITTER
84

FIG.18

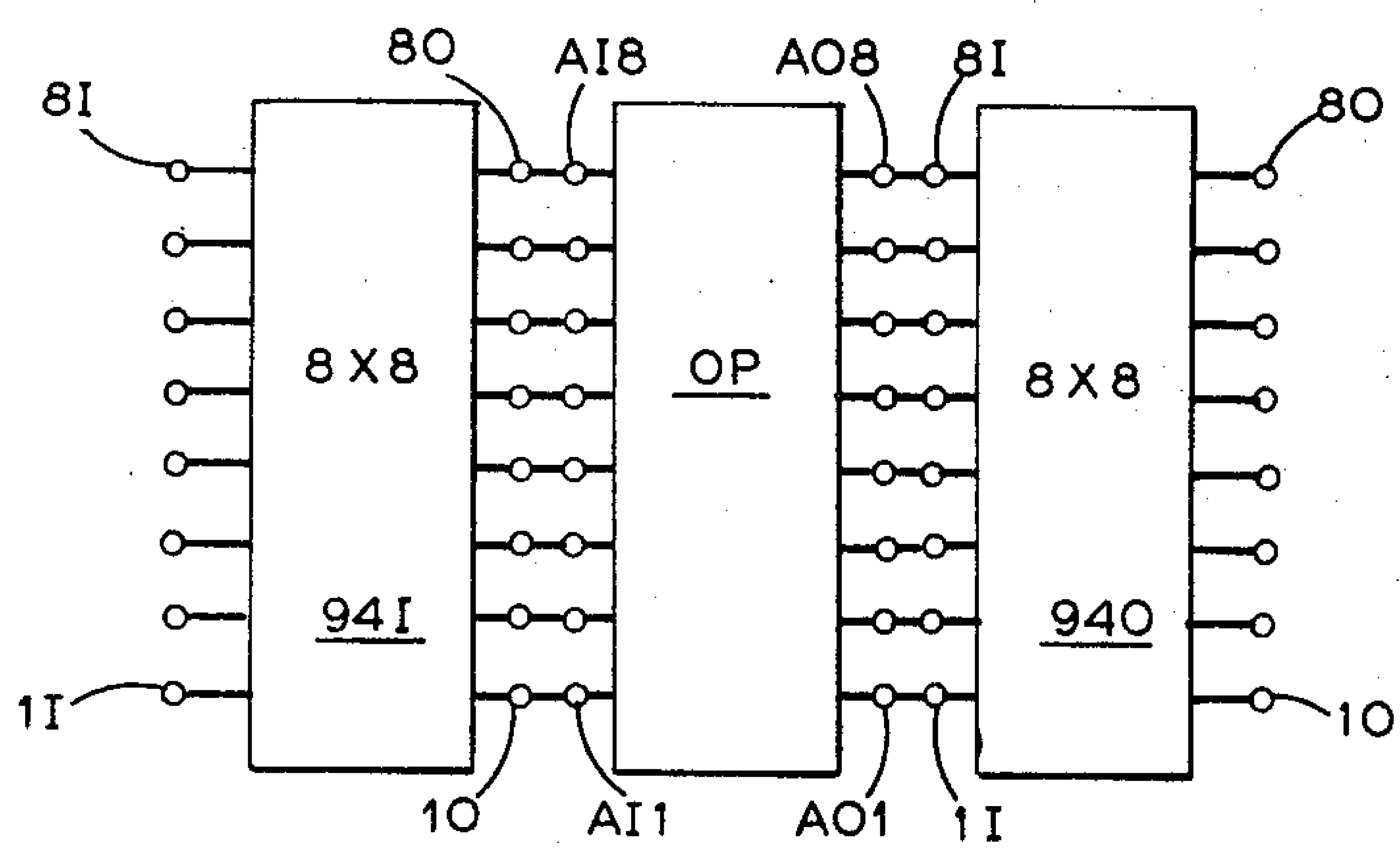


FIG. 20

MULTICHANNEL AMPLIFIER 98

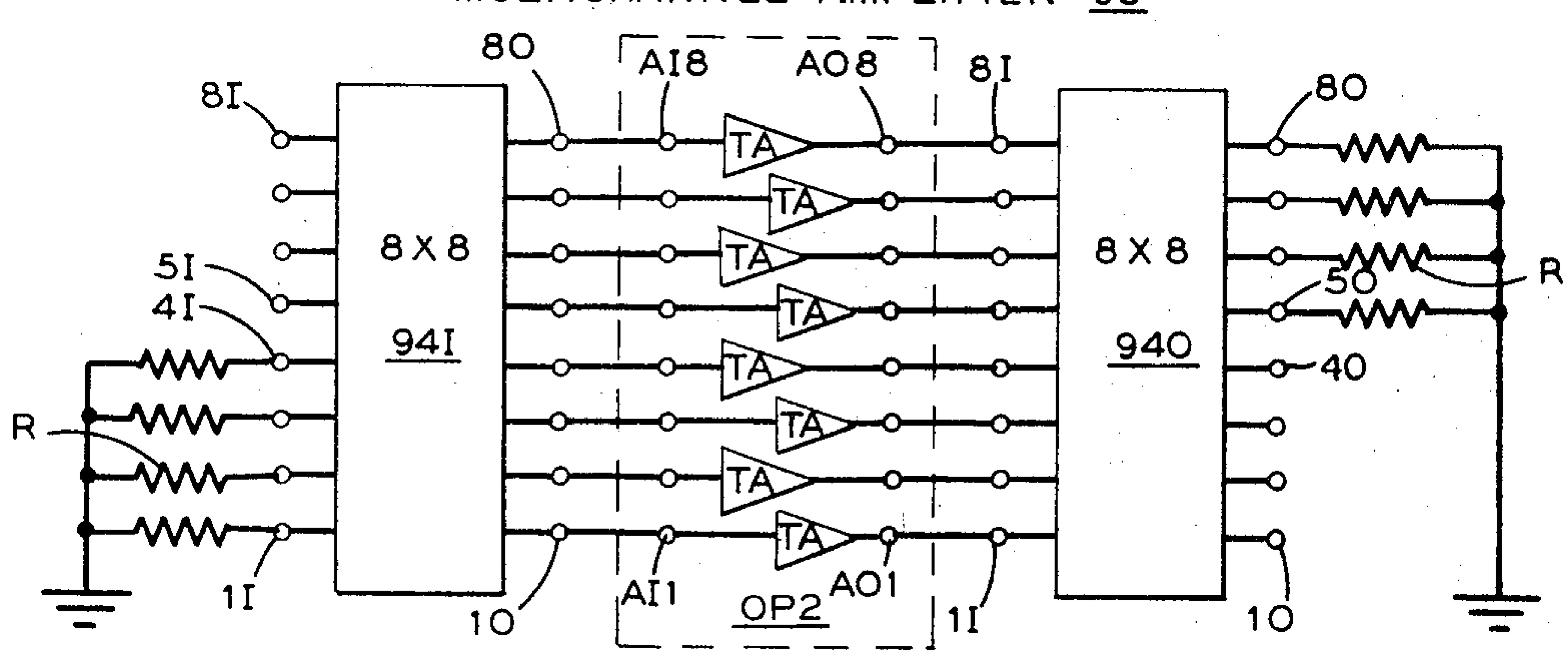


FIG. 19

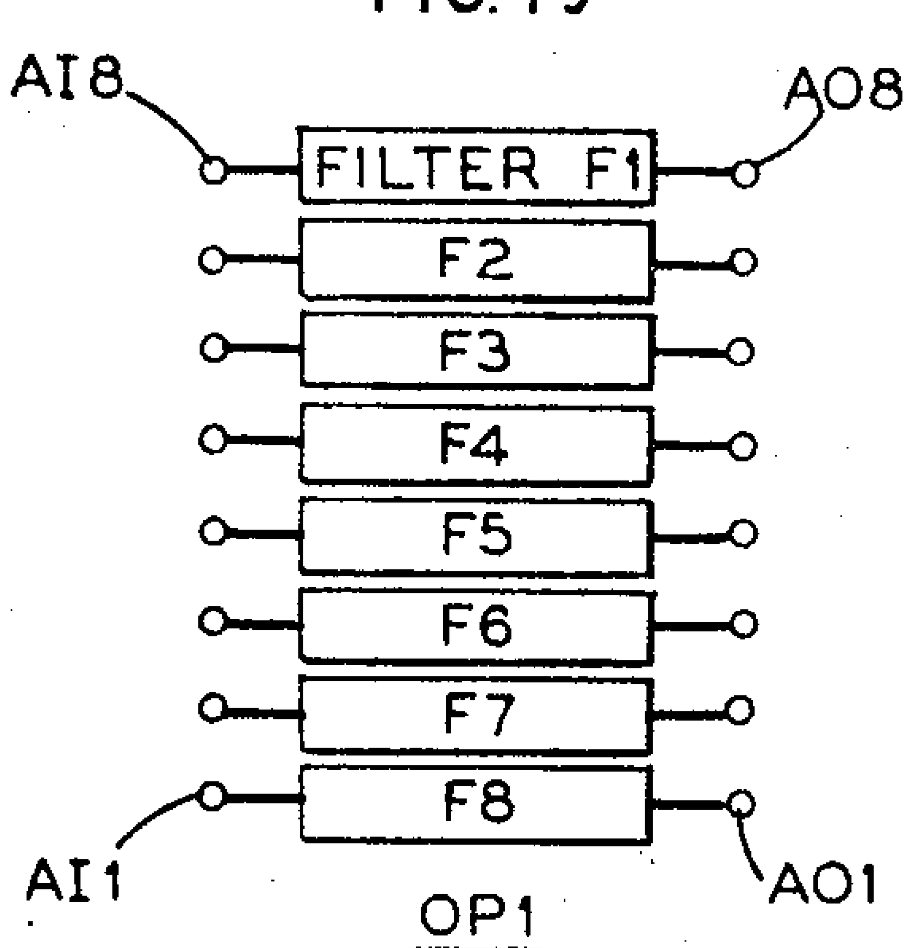
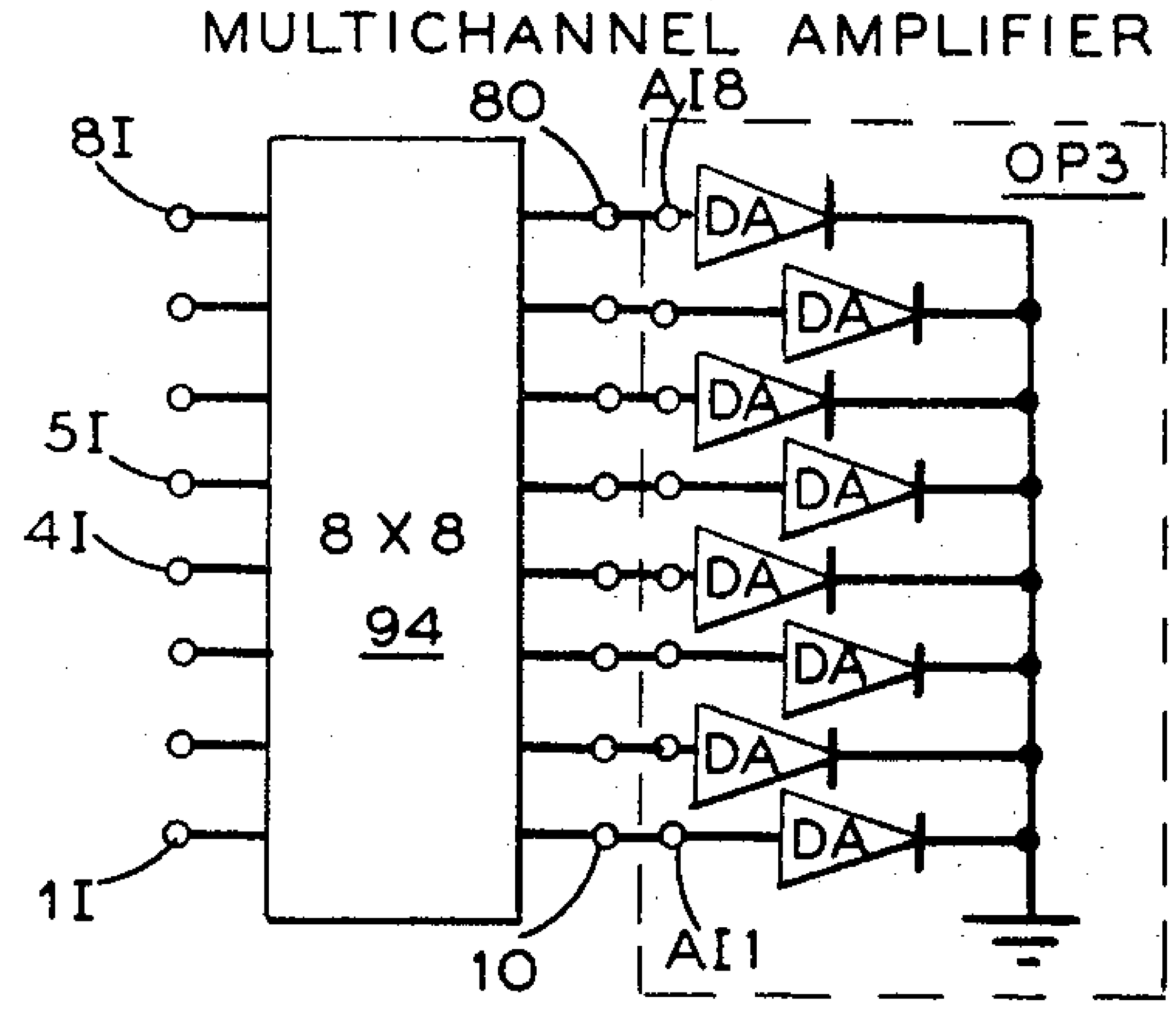


FIG. 21

MULTICHANNEL AMPLIFIER 99



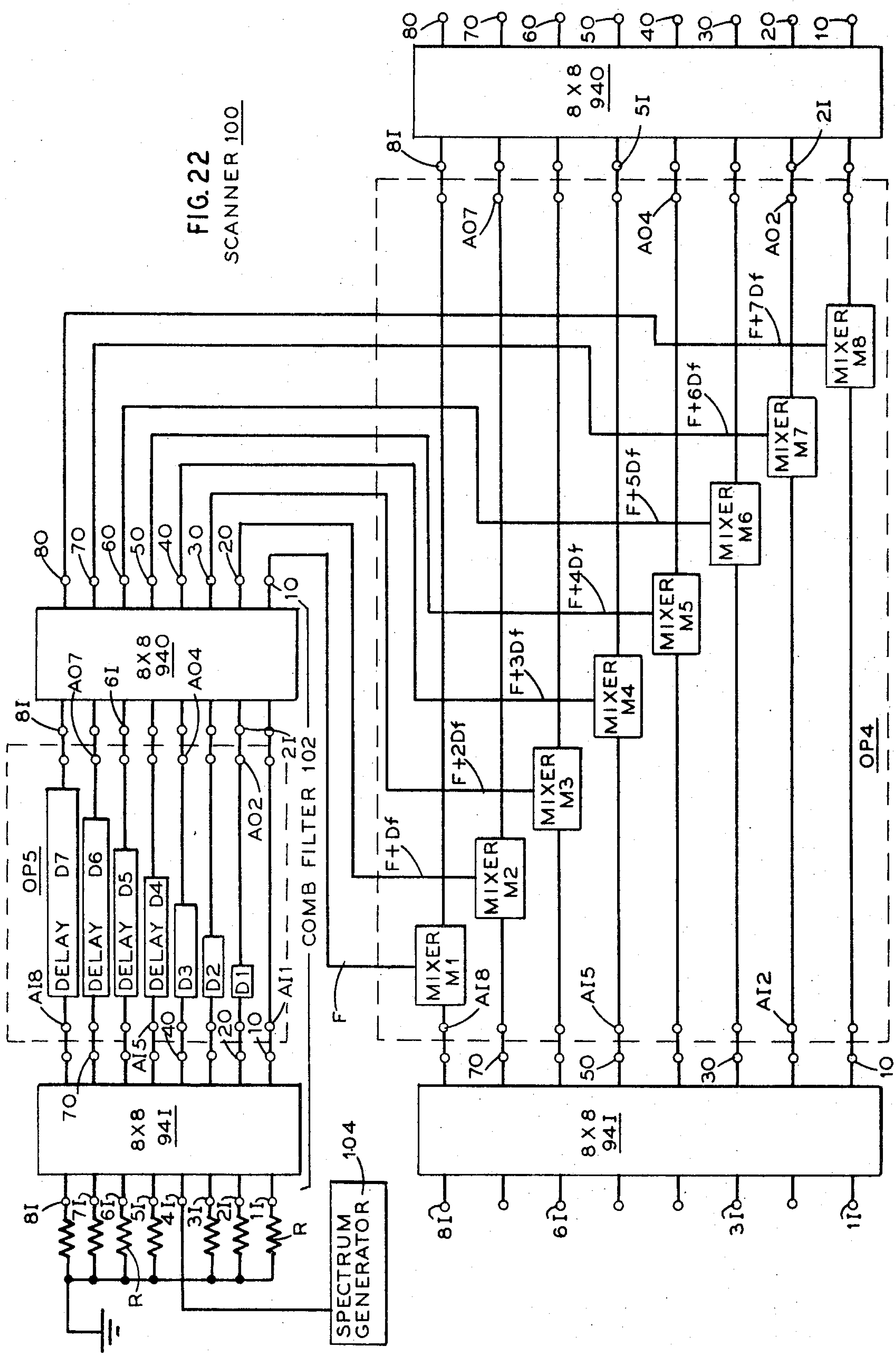
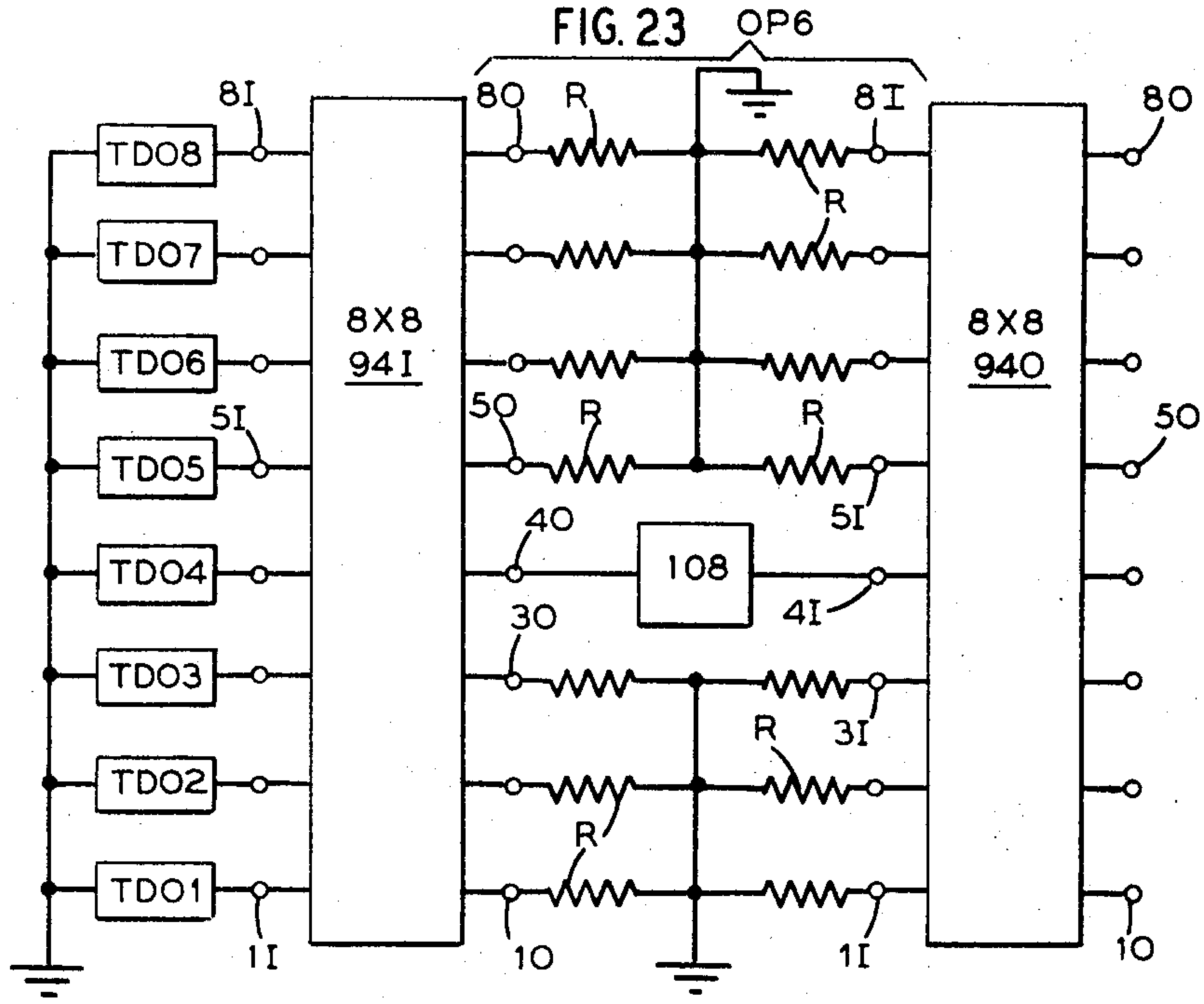


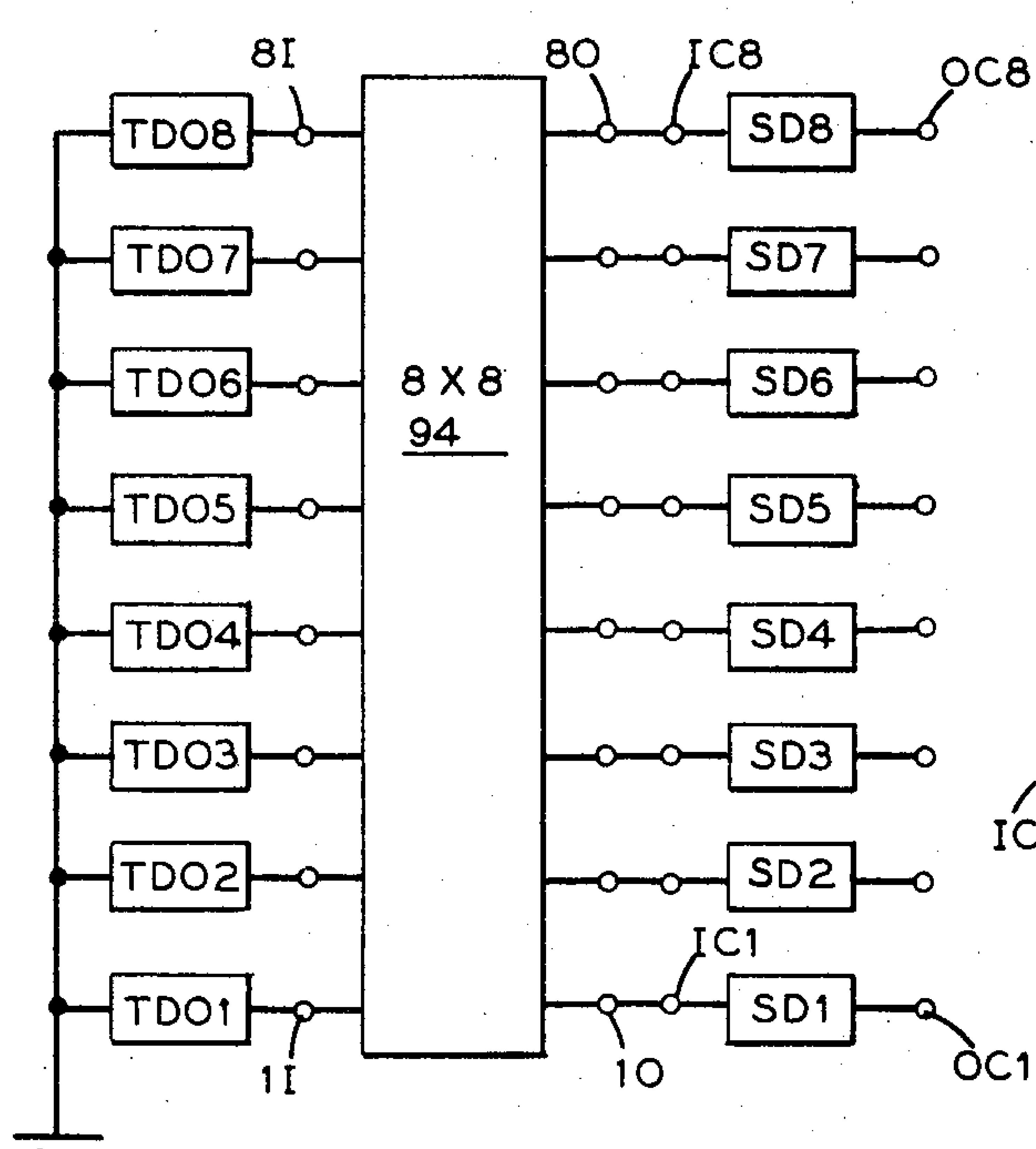
FIG. 22
SCANNER 100

FIG. 23



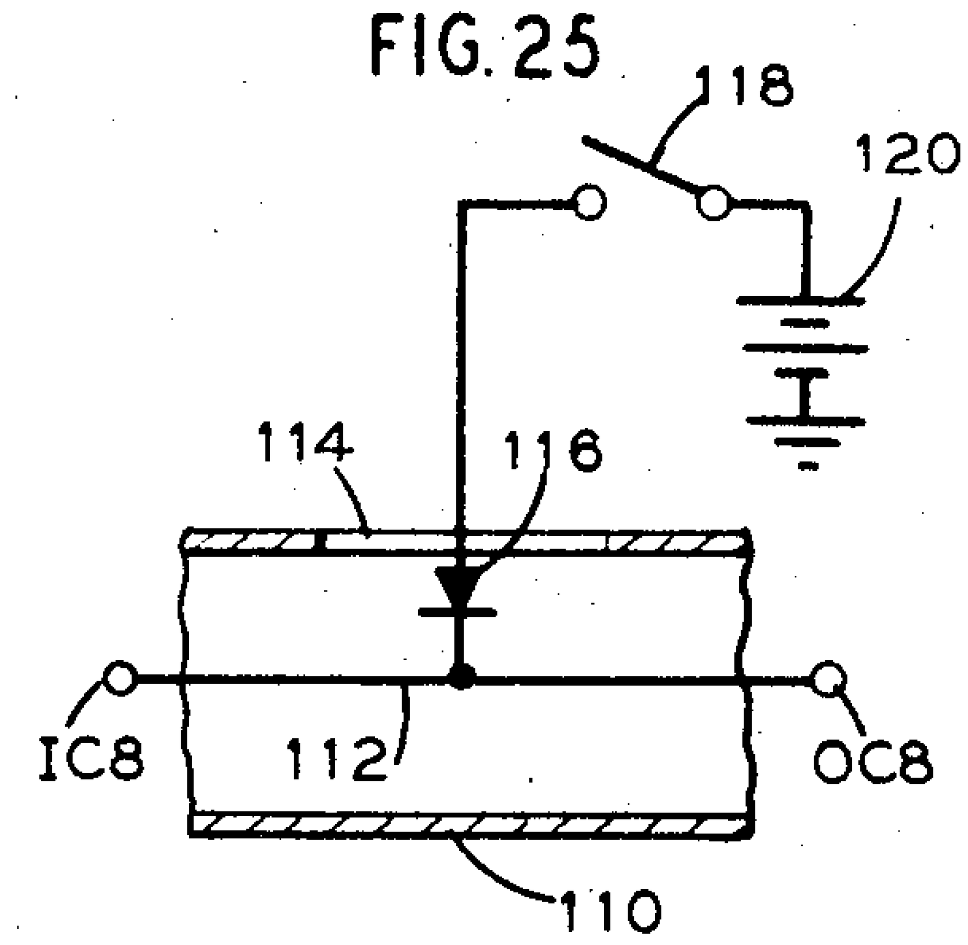
OSCILLATOR 106

FIG. 24



OSCILLATOR 107

FIG. 25



QUASI-OPTICAL SIGNAL PROCESSING UTILIZING HYBRID MATRICES

This invention pertains to the processing of information represented by the characteristics such as phase and amplitude signals and more particularly to the processing of such signals by quasi-optical techniques, and is a continuation of our copending application Ser. No. 570,232, filed Aug. 4, 1966, now abandoned.

Although optical analogies such as dielectric lenses, prisms and the like have heretofore been used to process microwave signals, such devices are continuous and are truly optical in character. By quasi-optical devices is meant devices which behave mathematically as lenses, prisms, stops, etc., but instead of being continuous devices, are in fact, discrete-transmission-line networks and components. The microwaves are always guided within a system of such devices. However, there are no continuous wave-fronts, but the microwaves are periodically sampled in space.

A heretofore known microwave network which performs quasi-optical signal processing is a "Butler Matrix" described in the article "Multiple Beam on Linear Arrays" by J.P. Shelton and K. S. Kelleher, Institute of Radio Engineers, Transactions on Antennas and Propagation (March, 1961). The Matrix is the microwave equivalent of the optical lens. The major difference between the two is that the Matrix is a "discrete lens". It has only a finite number of ports (signal transfer points) while the optical lens, of course, is continuous.

Optical lenses perform a spatial Fourier transform, while a Butler Matrix performs a folded sampled Fourier transform. The signals are sampled in the object and image planes because of the discrete nature of the Matrix. The focal planes of the Matrix are always the input and output ports. Thus, the focal length of the lens has no direct parallel in the Matrix. The equivalent of the focal length in the Matrix is the dimension of the Matrix, i.e., the number of ports.

The Butler Matrix was created to be a passive beam-forming matrix in a receiving array radar and acts as the lens in a refracting telescope. With radiators connected to the input or object ports and detectors at the output or image ports, the direction of an illuminated object can be determined by the angle of arrival of the reflected wave phase front.

A multiport Butler Matrix is a complicated microwave network. When the dimension of the Matrix exceeds 2 × 2, the number of components and their interconnections rapidly grows. Since any truly worthwhile device for quasi-optical signal processing relies on analog redundancy, i.e., power splitting between the channels, Matrices having dimensions of at least 4 × 4 are required.

Furthermore, it has been found that other microwave-network matrices can also be employed for quasi-optical microwave signal processing. These matrices are much simpler to fabricate. In addition, by following the teaching of the fabrication of these matrices the making of a Butler Matrix is greatly simplified.

It is, accordingly, a general object of one aspect of the invention to provide an improved microwave-network matrix.

It is another object of this aspect of the invention to provide an improved microwave-network matrix which is simpler than previously available matrices.

It is a further object of this aspect of the invention to provide a microwave-network matrix which readily lends itself to mass production techniques.

Briefly, this aspect of the invention contemplates a matrix for transforming microwave signals comprising at least four couplers. Each of the couplers includes first and second input ports and first and second output ports. There are means coupling the first input port to the first and second output ports for transferring substantially equal portions of microwave-signal power received at the first input port to the first and second output ports wherein the portions have different relative signal phases and also coupling the second input port to the first and second output ports for transferring substantially equal portions of microwave-signal power received at the second input port to the first and second output ports. Means couple one of the output ports of the first coupler to one of the input ports of a third coupler. Other means couple the other of the output ports of the first coupler to one of the input ports of a fourth coupler. Further means couple one of the output ports of a second coupler to the other of the input ports of the third coupler. And still further means couple the other of the output ports of the second coupler to the other of the input ports of the fourth coupler. At least one of the input ports of at least one of the first and second couplers receives a microwave signal and at least one of the output ports of at least one of the third and fourth couplers transmits a microwave signal. Such a matrix has a 4 × 4 dimension and becomes readily a building block for higher dimension matrices.

It should be noted that by using similar couplers which can be 90° hybrids and by virtue of the simple interconnections of the couplers, the matrices are ideally realizable by using shielded striplines and microstriplines. In such a case the devices lend themselves to conventional "printed" circuit techniques. In fact, features of this aspect of the invention are concerned with specific embodiments of the invention utilizing coupled-transmission-line couplers, branch-line couplers and coupled-transmission-line hybrid couplers.

Another feature of this aspect of the invention provides means for interconnecting the couplers without any actual physical crossovers when the couplers have the planar geometry of shielded striplines and microstriplines.

A further feature of this aspect of the invention provides a simplified 2 × 2 180° hybrid which can be used in higher dimension Butler Matrices.

The above described matrix as well as the Butler Matrix has the property of dividing the microwave-signal energy received at any input port and transferring equal portions of it to each of the output ports. The signals at the output ports will have a given phase code. The code is at least a function of the input port that was excited. Furthermore, if a second input port is excited it also transmits its received energy in equal quantities to the output ports with a given phase code. Since these matrices are linear the usual superposition of signals occurs. In addition, these matrices are reciprocal so that if all ports on one side of the matrix are excited with equal amplitude energy and the proper phase code, the energy will exit at a single port on the opposite side of the matrix. The port at which the energy exits depends on the phase code of the incident energy. Thus, two matrices of equal dimension connected in tandem perform an identity transformation. The identity in some cases will be a true isomorphic identity when 180° hybrids are employed, but in other cases, when 90° hybrids are employed, the identity will be of the "-mirror" type. In other words, the two matrices are equivalent to two similar lenses serially disposed in an optical path. It has been found that by operating on the signals in the distributed domain, ..e., the region between the output ports of a first matrix and the input ports of the second matrix, remarkable signal processing results are obtained. In addition, the devices for performing the operations can be unreliable active components or even passive components.

Thus, according to another aspect of the invention there is contemplated a microwave-signal-processing system comprising first and second phase-transform matrices. Each of the phase-transform matrices comprises at least four input ports and at least four output ports. Means connect the input ports to the output ports for transferring microwave power received at any one of the input ports in substantial equal quantities to each of the output ports with at least some of the voltages associated with the power having different signal-phase relationships. An operator matrix connects the first phase-transform matrix to the second phase-transform matrix. The operator matrix comprises at least one input port and at least one output port, and also means connecting the input ports to the output ports for changing a characteristic of signals received at the input ports. Means connect at least one of the output ports of the first phase-transform matrix to at least one of the input ports of the operator matrix; and means connect at least one of the output ports of the operator matrix to at least one of the input ports of the second phase-transform matrix. At least one of the input ports of the first phase-transform matrix receives a microwave signal; and at least one of the output ports of the second phase-transform matrix transmits a microwave signal. Hence, microwave-signal energy received at input ports of the first phase-transform matrix is transformed and enters a distributed domain where it is operated on by the operator matrix. The operator matrix can change the amplitude, phase, frequency or spatial distribution of the energy. The so-modified microwave energy is then fed through the second phase-transform matrix where a recombining or "refocusing" occurs.

In accordance with this aspect of the invention, there are presented features directed to providing filters, multichannel amplifiers, scanners, oscillators and switchable power sources. However, these are not the only capabilities of the device.

Other objects, features and advantages of the invention will be apparent from the following detailed description, when read with the accompanying drawings. The description and drawings set forth, by way of example and not limitation, the presently contemplated embodiments of the invention. In the drawings:

FIG. 1 is a functional or logical diagram of the 90° coupler building block used in the microwave-signal-processing apparatus;

FIG. 2 is a perspective view of a branch-line 90° coupler employing microstriplines as a realization of the coupler of FIG. 1;

FIG. 3 is a top plane view of a coupled-transmission-line 90° hybrid employing shielded striplines as a realization of the coupler of FIG. 1;

FIG. 4 is a sectional view taken along the line 4—4 of FIG. 3;

FIG. 5 is a sectional view taken along the line 5—5 of FIG. 3;

FIG. 6 is a sectional view taken along the line 6—6 of FIG. 3;

FIG. 7 is a perspective view of a coupled-transmission-line coupler employing shielded striplines as a further embodiment of the coupler of FIG. 1;

FIG. 8 is a functional diagram of a 180° hybrid coupler;

FIG. 9 is a functional diagram of a 2 × 2 coupler;

FIG. 10 is a functional diagram of a crossover matrix utilizing the 90° couplers of FIG. 1;

FIG. 11 is a functional diagram of a power splitter utilizing the 2 × 2 couplers of FIG. 9;

FIG. 12 is a functional diagram of a 4 × 4 phase-transform matrix built up from the 2 × 2 couplers of FIG. 9;

FIG. 13 is a functional diagram of a 4 × 4 phase-transform matrix of the Butler type built up from the 180° couplers of FIG. 8;

FIG. 14 is the symbolic representation of two coaxial transmission lines;

FIG. 15 is a symbol which represents the 4 × 4 phase-transform matrices of FIGS. 12 and 13;

FIG. 16 is a functional diagram of an 8 × 8 phase-transform matrix employing the 2 × 2 couplers of FIG. 9 and the 4 × 4 matrix of FIG. 15;

FIG. 17 is a symbolic representation of the 8 × 8 matrix of FIG. 16;

FIG. 18 is a functional diagram of a microwave-signal-processing system employing two of the 8 × 8 matrices of FIG. 17 and an operator matrix;

FIG. 19 is a schematic diagram of an operator matrix used in a filter amplifier;

FIG. 20 is a functional diagram of one embodiment of a multi-channel amplifier employing the 8 × 8 matrices of FIG. 17 and a plurality of transistor amplifiers in the operator matrix;

FIG. 21 is a functional diagram of another embodiment of the multichannel amplifier employing tunnel-diode amplifiers in the operator matrix;

FIG. 22 is a functional diagram of a scanner;

FIG. 23 shows a functional representation of a multichannel power source or oscillator;

FIG. 24 shows a functional representation of a switchable power source or oscillator; and

FIG. 25 shows a detail of FIG. 24.

Since a basic building block of most of the matrices is a 90° hybrid or 3 db. coupler, hereinafter called a coupler, it will be discussed first. A functional or logic diagram of the coupler is shown in FIG. 1. Coupler 30 has four ports 31, 32, 33 and 34. The coupler is linear and reciprocal. The coupler also has a given bandpass and has characteristic impedance at the ports. Unless otherwise indicated, the microwave-signal energy has frequencies within the bandpass of the coupler and the devices connected to the couplers have input and output impedances which match the characteristic impedances of the couplers. For the sake of definiteness the ports 31 and 32 are considered to be the input ports of the coupler and the ports 33 and 34 are considered to be the output ports of the coupler. Because of the reciprocal nature of the coupler, the input ports and output ports can be interchanged.

If a microwave signal is received at the first input port 31 the power or energy of the signal is split into two equal quantities. One quantity is fed to the first output port 33 and the other is fed to the second output port 34. The signal phase of the power transmitted from output port 33 is delayed by 90 electrical degrees or one-quarter of an operating wavelength from the signal phase of the power transmitted from output port 34. Thus, if the microwave power received at input port 31 is represented by the quantity A, the ports 33 and 34 transmit microwave energy having voltages represented by the quantities $-(1/\sqrt{2})\,jA$ and $(1/\sqrt{2})\,A$, respectively. Similarly, if a microwave signal is received at the second input port 32, the power of the signal is split into two equal quantities, one half of the power is fed to each of the output ports 33 and 34. The signal phase of the power transmitted from output port 34 is delayed by 90 electrical degrees or one-quarter of an operating wavelength from the signal phase of the power transmitted from output port 33. Thus, if the microwave power received at input port 32 is represented by the quantity B, the ports 33 and 34 transmit microwave power having voltages represented by the quantities $(1/\sqrt{2})\,B$ and $-(1/\sqrt{2})\,jB$, respectively. If microwave-signal power is simultaneously applied to input ports 31 and 32, signal superposition occurs because the coupler is linear. Therefore, by using the above indicated terminology, when microwave power received at input 31 is represented by A and the microwave power received at input port 32 is represented by B, output port 33 transmits microwave power having a voltage represented by $1/\sqrt{2}\,(-jA + B)$ and output port 34 transmits microwave power having a voltage represented by $1/\sqrt{2}\,(A - jB)$. Hence, the names 3 db. coupler or 90° hybrid. Two points are worth repeating: (1) any power received at an input port is divided equally between the output ports; and (2) the signals transmitted by the output ports have a phase difference.

There are several ways for physically realizing the coupler. The most economically worthwhile way for large microwave-signal-processing systems is by using shielded (double ground plane) striplines or microstriplines.

A microstripline embodiment is shown in FIG. 2 in the form of a branch-line coupler. Coupler 30A comprises a ground-plane element 35, a sheet of dielectric material 36 on the ground-plane element, and first and second linear conductors 37 and 38 on sheet 36. Linear conductor 37 electromagnetically cooperates with ground-plane element 35 to form a transmission line of the microstripline type; and linear conductor 38 electromagnetically cooperates with ground-plane element 35 to form another transmission line of the microstripline type. Linear conductors 37 and 38 are parallel and spaced from each other by one-quarter of an operating wavelength. Two further linear conductors 39 and 40 are on top surface of sheet 36. These conductors are mutually parallel, orthogonal to, and contact linear conductors 37 and 38. Conductors 39 and 40 are mutually spaced by one-quarter of an operating wavelength. Conductor 39 electromagnetically cooperates with ground-plane element 35 to form a transmission line of the microstripline type; and conductor 40 electromagnetically cooperates with ground-plane element 35 to form another transmission line of the microstripline type. The characteristic impedance of the transmission lines associated with linear conductors 37 and 38 is $\sqrt{2}$ times less than the characteristic impedances of the transmission lines associated with conductors 39 and 40. The characteristic impedance is controlled by the thickness of sheet 36 or preferably by the width of the conductors.

An input port 31A is connected to one end of linear conductor 38; the other input port 32A is connected to one end of linear conductor 37. The output ports 33A and 34A are connected to the other ends of linear conductors 37 and 38, respectively. Power transfer between the transmission lines associated with linear conductors 37 and 38 is via the transmission lines associated with linear conductors 39 and 40.

The branch-line coupler 30A has the advantage of ease of fabrication. It is readily made by using "printed circuit" techniques. For example, a standard printed-circuit substrate of glass, fiberboard or polyethylene has its surfaces covered with a conductor such as copper or silver. One surface is left unchanged to provide the ground-plane element. The other surface is photo-etched with the conductor pattern. The only possible limitation to the branch-line coupler is its bandwidth characteristic. It has a bandpass of approximately 10 percent of the operating frequency. However, except for specialized broadband applications this is no limitation.

For broadband-signal-processing applications it is more desirable to use the coupled-transmission-line hybrid shown in FIGS. 3, 4, 5 and 6. Coupler 30 B comprises a central sheet of dielectric material 50. On the top surface of sheet 50 is a first conductor 52 having three contiguous portions 52A, 52B and 52C angularly disposed with respect to each other. Conductor 52 is indicated by dot-dash lines in FIG. 3. On the bottom surface of sheet 50 is a second conductor 54 having three contiguous portions 54A, 54B and 54C, angularly disposed with respect to each other. Conductor 54 is indicated by dash lines in FIG. 3. Portions 52B and 54B are in parallel opposed relationship. The energy transfer between the two conductors 52 and 54 occurs only via these portions. The lengths of these portions are odd-integral multiples of quarter operating wavelengths. The angular disposition of the other portions is to prevent coupling at other regions. (It should be noted that the angles are exaggerated.) Disposed on top of conductor 52 is a sheet of dielectric material 56. On the top of sheet 56 is a ground-plane element 58. Disposed below conductor 54 is a sheet of dielectric material 60. Below sheet 60 is a ground-plane element 62.

Conductor 52 electromagnetically cooperates with ground-plane elements 58 and 62 to provide a transmission line of the shielded-stripline type; conductor 54 electromagnetically cooperates with ground-plane elements 58 and 62 to provide a transmission line of the shielded-stripline type. Input port 31B is connected to one end of conductor **52**; and input port **32B** is connected to one end of conductor **54**. The output ports **33B** and **34B** are coupled to the other ends of conductors **54** and **52**, respectively.

The coupler **30B** can be fabricated by photo-etching the conductors **52** and **54** on opposite sides of a dielectric substrate having surfaces of a conductive material using conventional printed-circuit techniques and sandwiching this substrate between two other substrates having conductive material on their outer surfaces. With such a coupler a 2:1 bandwidth is easily obtained and with moderate care an 8:1 bandwidth can be achieved.

The coupler can also be a coupled-transmission-line coupler as shown in FIG. **7**. Coupler **30C** comprises a sheet of dielectric material **64** whose bottom surface is covered with a ground-plane element **66**. On the top surface are two conductors **68** and **70**, each having three contiguous portions. The central portions **68B** and **70B** are substantially parallel and electromagnetically coupled to each other. The length of these portions is an odd-integral number of quarter-operating wavelengths. The end portions **68A** and **70A**, and **68C** and **70C** flare away from each other to minimize any electromagnetic coupling between these portions. On top of conductors **68** and **70** is another sheet of dielectric material **72** whose top surface is covered with a ground-plane element **74**. Conductor **68** and ground-plane elements **66** and **74** electromagnetically cooperate to form a transmission line of the shielded-stripline type. Similarly, conductor **70** and ground-plane elements **66** and **74** electromagnetically cooperate to form a transmission line of the shielded-stripline type. Energy flow from one transmission line to the other occurs in the coupling region defined by portions **68B** and **70B**. Input port **31C** is connected to one end of conductor **70** and output port **34C** is connected to the other end of conductor **70**. Input port **32C** is connected to one end of conductor **68** and input port **33C** is connected to the other end of conductor **68**.

Although in each of the embodiments of FIGS. **2** to **7** the ports are shown idealized, it should be realized that conventional stripline-to-coaxial line couplings can be employed as well as other lengths of matching stripline.

It should be noted that in each case the thickness of the conductors and the ground-plane elements has been exaggerated. It should also be realized in each embodiment that the sheets of dielectric material are primarily provided to maintain the required configuration geometry of the conductors and the ground-plane elements.

In building devices which are combinations of these couplers and other elements, the connections between the couplers and the elements will be shown idealized. However, it should be realized that conventional couplings, coaxial lines or striplines can be employed. In many cases, it is fruitful to connect the couplers by striplines which are printed on the substrates from which the couplers are fabricated to form an integrated package.

As a first example of the use of the coupler **30** as a building block, there will be described an improved 180° hybrid matrix. Such a matrix is similar to the above-described couplers in that the microwave-signal power received at each input port is divided and transmitted in equal halves to each of the output ports. The only difference is in the voltage phase relationship of the microwave-signal power transmitted from the output ports. In particular, the microwave signal received at the first input port is transmitted with the same phase from both output ports, whereas the microwave signal received at the second input port is transmitted with a 180° mutual phase difference from both output ports. Using the terminology employed above, if the first and second input ports received microwave-signal power represented by A and B, respectively, then the first and second output ports transmit microwave-signal power having voltages represented by $1/\sqrt{2}\,(A+B)$ and $1/\sqrt{2}\,(A-B)$, respectively.

A 180° hybrid **71** is shown in FIG. **8** utilizing the coupler **30**. The ports **31**, **32**, **33** and **34** are considered to be signal transfer points. The input ports of the matrix are ports **76** and **77** and the output ports are ports **78** and **79**. In order to obtain the proper signal-phase relationships between the signals transmitted from the output ports, combinations of the phasing devices **72** to **75** are used. The proper signal-phase relationships require that there be, both: (1) a 90° phase difference between the signals received at input port **77** and transferred to transfer point **31** and the signals received at input port **76** and transferred to transfer point **32**; and (2) a 90° phase difference between the signals received at transfer point **34** and transferred to output port **79** and the signals received at transfer point **33** and transferred to output port **78**. The first condition is satisfied by either introducing a 90° phase delay or introducing a 90° phase advance in the signal transferred from input port **77** to transfer point **31** while leaving the phase of the signal transferred from input port **76** to transfer point **32** unchanged. To obtain the 90° phase delay a quarter wavelength of transmission line is used as the phasing device **72** between input port **77** and transfer point **31** while input port **76** "merges" with transfer point **32**. To obtain the 90° phase advance, a quarter wavelength of transmission line is used as the phasing device **72** between input port **77** and transfer point **31**, while a half wavelength of transmission line is used as the phasing device **74** between input port **76** and transfer point **32**. If broad-banding is desired in the latter case, the phasing device **72** can be replaced by a Shiffman Phase Shifter. Since these same techniques can be employed for the phasing devices **73** and **75**, they will not be repeated for the sake of brevity.

Before proceeding with the discussion of building higher dimension matrices and other combinations, it is convenient to create a new functional symbol, a 2 × 2 coupler. The 2 × 2 coupler **80** shown in FIG. **9** can be either the 90° coupler **30** of FIG. **1** or the 180° coupler **71** of FIG. **8**.

The first example of the use of a plurality of 2 × 2 couplers is the crossover matrix **82** shown in FIG. **10**. Matrix **82** comprises two 90° couplers **30** connected in tandem. The output ports **102** and **101** of coupler **30I** are connected to the input ports **2I1** and **2I2** of coupler **300**, respectively. The input ports of matrix **82** are the input ports **1I1** and **1I2** of coupler **30I**; the output ports of matrix **82** are the output ports **201** and **202**. A microwave signal received at input port **111** is transmitted from output port **201**; a microwave signal received at port 112 is transmitted from output port 202. Thus, microwave signals, in effect, pass diagonally across the matrix. Such a matrix is highly desirable when the couplers are built up of printed striplines since it conveniently solves the topological problem of how to cross two signal paths without them intersecting.

FIG. 11 shows the power splitter 84 combining 2 × 2 couplers in a tree array. The power splitter 84 comprises the couplers 80A, 80B and 80C. The input ports 112, 211 and 312 of couplers 80A, 80B and 80C, respectively, are terminated with reflectionless-microwave-energy dissipation means in the form of mocrowave resistors R having resistances equal to the characteristic impedances of the input ports. The output port 102 of coupler 80A is connected to the input port 212 of coupler 80B, and the output port 101 is coupled to the input port 311 of coupler 80C. When microwave-signal power is received at the input port 111, it is divided and fed in 301 of coupler 80C and 202 and 201 of coupler 80B. The power splitter 84 divides the received microwave-signal power into four channels. Eight channel-power division can be obtained by adding another level of equal quantities and phase to the output ports 302 and couplers to the tree array.

It should be noted that power splitter 84 can act as a summer. Microwave-signal power is fed to ports 202, 201, 302 and 301 acting as input ports. All the received power is transmitted from port 111 acting as an output port, provided the phase code was proper for the inputs.

In FIG. 12 a 4 × 4 phase-transform matrix 90 is shown comprising four 2 × 2 couplers 80A-D. Coupler 80A is connected to couplers 80C and 80D; and coupler 80B is connected to couplers 80C and 80D. In particular, the output port 101 of coupler 80A is coupled to the input port 312 of coupler 80C and the output port 102 is connected via crossover 88 to input port 412 of coupler 80D; and the output port 201 of coupler 80B is coupled via crossover 88 to input port 311 of coupler 80C and output port 202 of coupler 80B is coupled to coupler 411. The input ports of the matrix 90 are input ports 111, 112, 211 and 212 of couplers 80A and 80B, respectively. The output ports of the matrix 90 are the output ports 301, 302, 401 and 402 of the couplers 80C and 80D. The crossover 88 can be as shown in FIG. 14 which represents two separate coaxial lines. In a "printed" array the crossover is preferably crossover matrix 82 of FIG. 10 wherein terminals C1, C2, C3 and C4 are respectively ports 111, 112, 201 and 202 of matrix 82.

FIG. 13 shows a 4 × 4 phase-transform matrix of the Butler type. Matrix 92 comprises 180° couplers 80A to 80D which are the 180° hybrids 71 of FIG. 8. The couplers 80 are connected in the same way as the couplers 80 of FIG. 12, as indicated by the similar reference characters, with one exception, a 90° phase shifter is connected between output port 101 of coupler 80A and the input port 312 of coupler 80C.

The symbolic representation of the 4 × 4 matrices 90 and 92 is indicated by 4 × 4 matrix 91 in FIG. 15 having input ports 111, 112, 113 and 114 and output ports 101, 102, 103 and 104.

An 8 × 8 phase-transform matrix 94 is shown in FIG. 18 comprising 4 × 4 matrices 91A and 91B, and 2 × 2 couplers 80A to 80D. One output port of matrix 91A is coupled to one input port of each of the 2 × 2 couplers, respectively; one output port of matrix 91B is coupled to the other input port of each of the 2 × 2 couplers, respectively. The input ports of the matrices 91A and 91B are the input ports of the matrix 94, and the output ports of the 2 × 2 couplers 80A to 80D are the output ports of the matrix 94. If the 8 × 8 phase-transform matrix is to be of the Butler type, the 4 × 4 matrices are the 180° coupler matrices 92 of FIG. 13, and the 2 × 2 couplers are the 2 × 2 180° coupler matrices 71 of FIG. 8. Furthermore, a 135° phase shifter is connected between output port 101 of matrix 91A and input port 112 of coupler 80A; a 90° phase shifter is connected between output port 102 of matrix 91A and input port 212 of coupler 80B, and a 45° phase shifter is connected between output port 103 of matrix 91A and input port 312 of coupler 80C. The symbolic representation of the 8 × 8 matrix 94 is shown in FIG. 17 having eight input ports 1I to 8I and eight output ports 1O to 8O.

It should be noted that not only is the 2 × 2 coupler reciprocal but the crossover matrix 82, the 4 × 4 matrices 90 and 92 and the 8 × 8 matrix 94 are reciprocal. Hence, the input and output ports are interchangeable.

There will now be discussed several microwave-signal-processing systems utilizing the phase-transform matrices in combination with different operator matrices. The general combination is shown in FIG. 18 comprising an input phase-transform matrix 94I which receives microwave signals at its input ports 1I to 8I and transfers these signals, transformed, from its output ports to the distributed domain. The transformed signals are received by the input ports AI1 to AI8 of the operator matrix OP where they are operated on to change characteristics of the signals. The operated on signals are transferred via the output ports AO1 to AO8 of the operator matrix OP and the input ports 1I to 8I of the output phase-transform matrix 94O. The signals are "inversely" transformed and transmitted from the output ports 1O to 8O.

The operator matrix can perform a transfer operation which is passive or active, spatially dependent or independent, dispersive or nondispersive, time varying, etc. The transfer may be an amplitude function or a phase function or both.

An operator matrix which performs a frequency-dependent transfer function is shown in FIG. 19. The operator matrix OP1 comprises band limiting filters F1 to F8. If the filters are identical then the output signals are only frequency dependent. If the characteristics of the filters vary across the "aperture" then the signals are both frequency and spatially dependent.

The potency of the concepts of the invention will be apparent from the following discussion of the multichannel amplifiers 98 and 99 of FIGS. 20 and 21. Conventional techniques for achieving multichannel devices generally use one amplifier per channel. If an amplifier fails, a channel is lost. Furthermore, if it is required that channel-to-channel gain and phase characteristics be identical, a great strain is placed on the amplifiers used in conventional circuits since they must be made to have identical characteristics. This is extremely difficult and expensive in bulk devices and becomes almost impossible with micro-electronic devices. These problems do not exist with the multichannel amplifiers 98 and 99.

Amplifier **98** is a four channel amplifier comprising: an input 8 × 8 phase-transform matrix **94I** which receives signals at its input ports **5I** to **8I** and has its input ports **1I** to **4I** loaded with resistors R having resistances equal to the characteristic impedance; an operator matrix OP2 comprising eight conventional transistor amplifiers TA, the inputs of the amplifiers TA are connected to the input ports AI1 to AI8 and the outputs of the amplifiers TA are connected to the output ports AO1 to AO8 of the matrix OP2; and an output 8 × 8 phase-transform matrix **94O** which transmits signals from its output ports **1O** to **4O** and has its output ports **5O** to **8O** loaded with resistors R having resistances equal to the characteristic impedance. The output ports **1O** to **8O** of matrix **94I** are connected to the input ports AI1 to AI8 of matrix OP2. The output ports AO1 to AO8 of matrix OP2 are connected to input ports **1I** to **8I** of matrix **94O**.

A signal received at input port **8I** of matrix **94I** is divided into eight equal parts. Each part is amplified by one of the transistor amplifiers TA. The amplified parts are refocused by matrix **94O** and transmitted from its output port **1O**. Similarly, a signal received at input port **5I** of matrix **94I** is divided among the eight transistor amplifiers and then refocused so that the amplified signal appears at output port **4O** of matrix **94O**. It should be noted that only half of the input ports of matrix **94I** and only half of the output ports of matrix **94O** are used as signal transfer means. The remaining ports are terminated with the load resistors R to absorb reflections from the transistor amplifiers. Because of the power dispersion and "focusing", the amplifiers can have reasonably randomly distributed gain and phase characteristics and still identical channel-to-channel characteristics are obtained. Furthermore, because there is analog redundancy in the distributed domain the failure of an amplifier does not cause the loss of a channel. Instead, the crosstalk between channels increases slightly and the gain of all channels drops slightly. The situation is similar to the case where a partial stop is placed between two lenses. In general, only amplitude is lost, but all the information is transmitted.

The multichannel amplifier **99** of FIG. **21** employs only one 8 × 8 phase-transform matrix **94** and an operator matrix OP3 employing eight conventional tunnel-diode amplifiers DA. The matrix **94** must be of the type built from the couplers **30** of FIG. **1** and the matrices **90** of FIG. **12**. The ports **5I** to **8I** are the input ports of the amplifier and the ports **1I** to **4I** are the output ports of the amplifier. The ports **1O** to **8O** are input-output ports of the matrix **94** and are connected to the ports AI1 to AI8 of matrix OP3 which are the signal terminals of the tunnel-diode DA. of the tunnel-diode amplifiers DA. A signal received at port **8I** splits equally between the eight amplifiers DA. The amplified signal is reflected back into the matrix **94** and exits from port **1I** Similarly, a signal received at port **5I** is amplified and transmitted from port **4I**, etc.

The scanner **100** (FIG. **22**) is an example of an operator matrix which is a phase function of time and position. The scanner **100** comprises an input 8 × 8 Butler phase-transform matrix **94I**, an operator matrix OP4, and an output 8 × 8 Butler phase-transform matrix **49O**. Signals received in parallel at the input ports **1I** to **8I** of matrix **94I** are serially transferred from each one of the output ports **1O** to **8O** of output matrix **94O**. If the signals received at input ports **1I** to **8I** are represented by the values *h, g, f, e, d, c, b* and *a*, respectively, then the following table gives the sequence of signals transmitted from the output ports of output matrix **94O**.

TABLE I

Port	Signal sequence
1o	*h, a, b, c, d, e, f, g, h, a, . . .*
2o	*g, h, a, b, c, d, e, f, g, h, . . .*
3o	*f, g, h, a, b, c, d, e, f, g, . . .*
4o	*e, f, g, h, a, b, c, d, e, f, . . .*
5o	*d, e, f, g, h, a, b, c, d, e, . . .*
6o	*c, d, e, f, g, h, a, b, c, d, . . .*
7o	*b, c, d, e, f, g, h, a, b, c, . . .*
8o	*a, b, c, d, e, f, g, h, a, b, . . .*

The operator matrix OP4 comprises eight conventional mixers M1 to M8. Each of the mixers has a signal input connected to one of the input ports AI1 to AI8 and a signal output connected to one of the output ports AO1 to AO8 of the matrix OP4. In addition, each of the mixers has a mixing-signal input which receives mixing signals that are displaced from each other by equal frequency differences Df. For example, the mixing signal received by mixer M1 has a frequency F, that received by mixer M2 has a frequency F + Df, that received by mixer M3 has a frequency of F + 2 Df, . . . , and that received by mixer M8 has a frequency of F +7 Df. The frequency differences should be constant from mixer to mixer and should progressively change across the aperture.

The mixing signals can be obtained from the comb filter **102** which is driven by spectrum generator **104**. The comb filter **102** is itself another example of a microwave-signal-processing system utilizing the teachings of the invention. Filter **102** comprises the input 8 × 8 Butler phase-transform matrix **94I** the operator matrix OP5, and the output 8 × 8 Butler phase-transform matrix **94O**.

All of the input ports **1I** to **8I**, except port **4I** of matrix **94I**, are terminated by resistors R having resistances equal to the characteristic impedances of the ports. The output ports **1O** to **8O** of matrix **94I** are connected to the input ports AI1 to AI8 of operator matrix OP5, respectively. Matrix OP5 has eight channels which are delayed by progressively increasing equal increments of time. For example, channel **2** is delayed by an increment *d* with respect to channel **1**, channel **3** by increment 2*d*, channel **4** by increment 3*d*, . . . , channel **8** by increment 7*d*, where *d* is an increment of time. The time delays can be accomplished by suitable lengths of transmission line D1 to D7. The output ports AO1 to AO8 of matrix OP5 are connected to the input ports **1I** to **8I** respectively of output matrix **94O**. The operator matrix OP5 can be considered as a discrete time delay "wedge" and is a phase function of space and frequency. The comb filter **102** performs the same function as an optical prism and two lenses. A broadband signal introduced at one of the input ports, say **4I**, of matrix **94I** is spread equally to the output ports **1O** to **8O** of matrix **94I**. The phase slope across the output ports of matrix **94I** will depend on which input port is excited. All of the frequencies present at the input port are present at each of the output ports of matrix **94I**. It is the power which is divided to the output ports. On passing through the time "wedge" (prism) presented by matrix

OP5 each frequency component is given a different phase slope (across the input ports 1I to 8I of matrix 94O) and is therefore focused at different output ports 1O to 8O of matrix 94O. This is the exact analogy of the creation of a rainbow from white light by a prism.

The spectrum generator **104** can be a conventional broad-band pulse generator.

FIG. **23** shows one embodiment of a multichannel power source or oscillator **106**. The oscillator **106** can be divided into two parts: a wavefront filter comprising input 8 × 8 phase-transform matrix **94I**, an operator matrix **OP6**, and an output matrix **94O**, serially connected in the usual manner; and a multi-channel-signal source comprising eight parallel-operating tunnel-diode oscillators TDO8 to TDO8.

Operator matrix **OP6** is primarily a plurality of reflectionless terminating resistors R connected to each of the output ports, except port 4O, of matrix **94I** and connected to each of the input ports, except port 4I of matrix **94O**. Transfer means **108** connects output port 4O to input port 4I. The operator matrix **OP6** is equivalent to an optical aperture which selectively transmits only the energy focused to that aperture. Thus, if a wavefront impinges on the input ports 1I to 8I of matrix **94I**, the operator matrix **OP6** transmits only waves with a specific phase slope and absorbs all others. If the aperture is at the center ports (the four or five ports) then only the wave with zero phase slope will be transmitted.

The wavefront is generated by the tunnel-diode oscillators TDO1 to TDO8. Assume that initially the oscillators are randomly phased with respect to each other. Then roughly one-eighth of the incident energy passes through output port 4O. The remainder is absorbed by resistors R. And assume that the transfer means **108** is partially reflective (a stub, for example). A part of the transmitted energy is reflected back through the matrix **94I** to each of the tunnel-diode oscillators. The reflected energy represents an average of the oscillator signals and tends to pull the oscillators together. As it does so, more of the total energy appears at port 4O and the pulling effect is enhanced until finally the oscillators are phase locked to an average center frequency at which time all the energy is focused to the port 4O. The unreflected part of the energy passes through means **108** to input port 4I of matrix **94O** which acts as a power splitter dividing the energy over eight channels by transmitting the energy from output ports 1O to 8O.

The oscillator has several advantages. First, if one of the tunnel-diode oscillators fails, only one-eighth of the output power is lost. Second, since the noise generated by each of the tunnel-diode oscillators is incoherent, it divides equally among the output ports of matrix **94I** where it is absorbed by the terminating resistors except for port 4O. Therefore, the signal-to-noise ratio is eight times greater than for a single oscillator. Third, the frequency stability of the overall system is superior to that of a single oscillator if the sources of frequency drift are independent, since the operating frequency is an average center frequency.

Now, if the output matrix **94O** is omitted there is obtained a single coherent output signal from the transfer means **108**. In addition, if each output port is terminated by a characteristic impedance which can be a transmission line of the same characteristic impedance feeding a signal utilization device having an input impedance equal to the characteristic impedance, it is possible to switch the output energy to a particular output port by temporarily making the load on the selected port partially reflective. The oscillator will lock on that port even after the reflection is removed and stay locked until another port is made partially reflective.

FIG. **24** shows such a switchable power source in the form of oscillator **107**. Oscillator **107** is the same as oscillator **106** except that the output matrix is deleted and each output port of matrix **94** is connected to a switchable discontinuity SD. A typical discontinuity SD8 is shown in FIG. **25**. It comprises a coaxial line comprising outer conductor **110** and central conductor **112** connected to output port 8O of matrix **94**. There is an opening **114** in conductor **110** to allow the connection of the anode of diode **116** to the central conductor **112**. The cathode of diode **116** is connected to a switchable-bias-voltage source shown schematically as a switch **118** and a battery **120**. Of course, the switchable-bias-voltage source in a practical system would include electronic switching. In any event, as long as the diode is not biased to the conducting state there is no discontinuity in the line and it is reflectionless. However, when switch **118** is closed the diode **116** is conductive and an RF short is developed in the line and it becomes reflective.

In view of the large number of examples cited and the various embodiments disclosed, there will now be obvious to those skilled in the art many modifications and variations which practice the invention and satisfy many or all of its objects. However, such modifications and variations will come within the spirit of the invention as defined by the appended claims.

What is claimed is:

1. The method of processing a plurality of alternating-current microwave signals being received in parallel and each having frequency, phase and amplitude parameters comprising the steps of transforming each one of the alternating-current microwave signals into another plurality of parallel phase-transformed alternating-current microwave signals having frequency, phase and amplitude parameters, each of said phase-transformed alternating-current microwave signals having a phase which is different from the phase of at least another phase-transformed alternating-current microwave signal and including a portion of the microwave energy of each of the received alternating-current microwave signals whereby a folded sampled Fourier transform is performed on the received alternating-current microwave signals, modifying at least one of said parameters of each of said parallel phase-transformed alternating-current microwave signals, and inversely transforming the parameter-modified parallel phase-transformed alternating current signals to provide a further plurality of parallel output alternating-current microwave signals.

2. A microwave-signal processing system comprising: a first power dividing and phase-transforming matrix; said first power dividing and phase-transforming matrix comprising a set of at least four input ports and a set of at least four output ports, and power dividing and phase shifting means reciprocally coupling each port of one set of ports to every port of the other set of ports for transferring at least some fractional quantity of any microwave signal received at any one port of one set of ports to every port of the other set of ports with at least some of the fractional quantities of microwave signal having different signal-phase relationships; a second power dividing and pahse-transforming matrix identical to said first power dividing and phase-transforming matrix, said second power dividing and phase-transforming matrix comprising a set of at least four input ports and a set of at least four output ports, and power dividing and phase shifting means reciprocally coupling each port of one set of ports to every port of the other set of ports for transferring at least some fractional quantity of any microwave signal received at any one port of one set of ports to every port of the other set of ports with at least some of the fractional quantities of microwave signal having different signal-phase relationships; an operator matrix comprising at least one input port and at least one output port; means for connecting said one input port only to said one output port for changing a characteristic of a microwave signal received at said input port when transferred to said output port; means for connecting at least one of the output ports of said first power dividing and phase-transforming matrix to the input port of said operator matrix; and means for connecting the output port of said operator matrix to at least one of the input ports of said second power dividing and phase-transforming matrix; at least one of the input ports of said first power dividing and phase-transforming matrix being adapted to receive a microwave signal; and at least one of the output ports of said second power dividing and phase-transforming matrix being adapted to transmit a microwave signal.

3. The microwave-signal-processing system of claim 2 further comprising a substantially reflectionless microwave-energy-dissipation means connected to each of the remaining input and output ports.

4. The microwave signal processing system of claim 2 wherein said first power dividing and phase-transforming matrix has *n* output ports and said second power dividing and phase-transforming matrix has *n* input ports, said operator matrix has *n* input ports and *n* output ports, each one of said *n* input ports of said operator matrix being connected to a different one of said *n* output ports of said operator matrix, respectively, means for connecting each one of said *n* output ports of said first power dividing and phase-transforming matrix to a different one of said *n* input ports of said operator matrix, respectively, and means for connecting each one of said *n* output ports of said operator matrix to a different one of said *n* input ports of said second power dividing and phase-transforming matrix, respectively.

5. The microwave-signal processing system of claim 2 wherein said first and second power dividing and phase-transforming matrices have a given frequency pass band, and said power dividing and phase shifting means thereof transfer the signals received at any one of the input ports of one of said power dividing and phase-transforming matrices to all output ports of the same power dividing and phase-transforming matrix as long as the received microwave signals have frequencies within said given frequency pass band so that each output port of said same phase-transforming matrix transmits microwave signals having all the frequencies of the microwave signal received by any one of the input ports of said one power dividing and phase-transforming matrix.

6. The microwave-signal processing system of claim 2 wherein a plurality of the input ports of said first power dividing and phase-transforming matrix are adapted to receive microwave signals and a plurality of output ports of said second power dividing and phase-transforming matrix are adapted to transmit microwave signals.

7. The microwave-signal-processing system of claim 2 wherein said operator matrix comprises a plurality of microwave signal amplifiers, each having an input and an output, said input being an input port of the operator matrix and said output being an output port of said operator matrix, means for connecting each of the output ports of said first power dividing and phase-transforming matrix to the input of one of said microwave-signal amplifiers, respectively, and means for connecting each of the corresponding input ports of said second power dividing and phase-transforming matrix to the output of one of said microwave-signal amplifiers, respectively, at least two of the input ports of said first power dividing and phase-transforming matrix being adapted to receive different microwave signals and at least two of the output ports of said second power dividing and phase-transforming matrix being adapted to transmit different microwave signals whereby said microwave-signal-processing system is a multichannel amplifier.

8. The microwave-signal processing system of claim 7 wherein said first and second power dividing and phase-transforming matrices have $2n$ input ports and $2n$ output ports, *n* of the input ports of said first power dividing and phase-transforming matrix being adapted to receive a microwave signal, *n* corresponding output ports of said second power dividing and phase-transforming matrix being adapted to transmit a microwave signal, and further comprising a plurality of substantially reflectionless microwave-power-dissipation means each connected to one of the remaining input and output ports, respectively.

9. The microwave-signal processing system of claim 8 wherein said operator matrix comprises *n* microwave-signal amplifiers each having an input terminal and an output terminal, means for connecting the input terminal of each signal amplifier to a different input port of said operator matrix, respectively, and means for connecting the output terminal of each signal amplifier to a different output port of said operator matrix, respectively, whereby there are *n* parallel amplifier channels in said operator matrix.

10. The microwave-signal-processing system of claim 2 wherein said operator matrix comprises a plurality of signal-delay means, each of said signal-delay means having an input terminal and an output terminal, means for connecting each of the input terminals to one of the output ports of said first power dividing and phase-transforming matrix, respectively, means for connecting each of the output terminals to one of the input ports of said second power dividing and phase-transforming matrix, respectively, and further comprising a substantially reflectionless microwave dissipation means connected to all but one of the input ports of said first power dividing and phase-transforming matrix, said one input port being adapted to receive

microwave energy having a spectrum of frequencies and the output ports of said second power dividing and phase-transforming matrix being adapted to transmit microwave-energy whereby said microwave-signal-processing system is a comb filter.

11. The microwave-signal-processing system of claim 10 wherein each of said signal-delay means has a different time delay.

12. The microwave-signal-processing system of claim 11 wherein the difference in the time delays is an integral multiple of a given time delay.

13. The microwave-signal-processing system of claim 12 wherein the time delays sequentially increase.

14. The microwave-signal-processing system of claim 2 wherein said operator matrix comprises a plurality of microwave-signal mixers, each of said microwave-signal mixers including a signal input, a signal output and a mixing-signal input, means for connecting each of the signal inputs of said microwave-signal mixers to one of the output ports of said first power dividing phase-transforming matrix, respectively, means for connecting each of the signal outputs to one of the input ports of said second power dividing phase-transforming matrix, respectively, and means for applying a different frequency microwave-mixing signal to each of the mixing-signal inputs, respectively, the input ports of said power dividing phase-transforming matrix being adapted to receive microwave signals and at least one of the output ports of said second power dividing phase-transforming matrix being adapted to transmit a microwave signal whereby said microwave-signal-processing system is a scanner.

15. The microwave-signal-processing system of claim 14 wherein the frequencies of the microwave-mixing signals are offset from each other by an integral multiple of *n* Hertz.

16. The microwave processing system of claim 15 wherein the microwave-mixing signals have frequency differences which sequentially increase.

17. The microwave-signal processing system of claim 2 further comprising a plurality of microwave-signal oscillators, means for connecting each of the microwave-signal oscillators to one of the input ports of said first power dividing and phase-transforming matrix, said operator matrix comprising a partially reflective microwave-signal transmission means including an input and an output, means for connecting said input to one of the output ports of said first power dividing and phase-transforming matrix, means for connecting said output to one of the input ports of said second power dividing phase-transforming matrix, a substantially reflectionless microwave-energy dissipation means connected to each of the remaining input ports of said second power dividing and phase-transforming matrix and to each of the remaining output ports of said first power dividing and phase-transforming matrix, at least one of the output ports of said second power dividing and phase-transforming matrix being adapted to transmit a microwave signal.

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