United States Patent

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[54] **MICROWAVE IMPEDANCE MATCHING SYSTEM**
12 Claims, 9 Drawing Figs.

[52] **U.S. Cl.** ..... **333/17,** 328/155, 329/160, 333/31 A, 333/33, 333/98 R
[51] **Int. Cl.** **H01p 5/08,** H03h 7/40
[50] **Field of Search** ..... 333/17, 17 A, 33; 343/861

[56] **References Cited**

UNITED STATES PATENTS

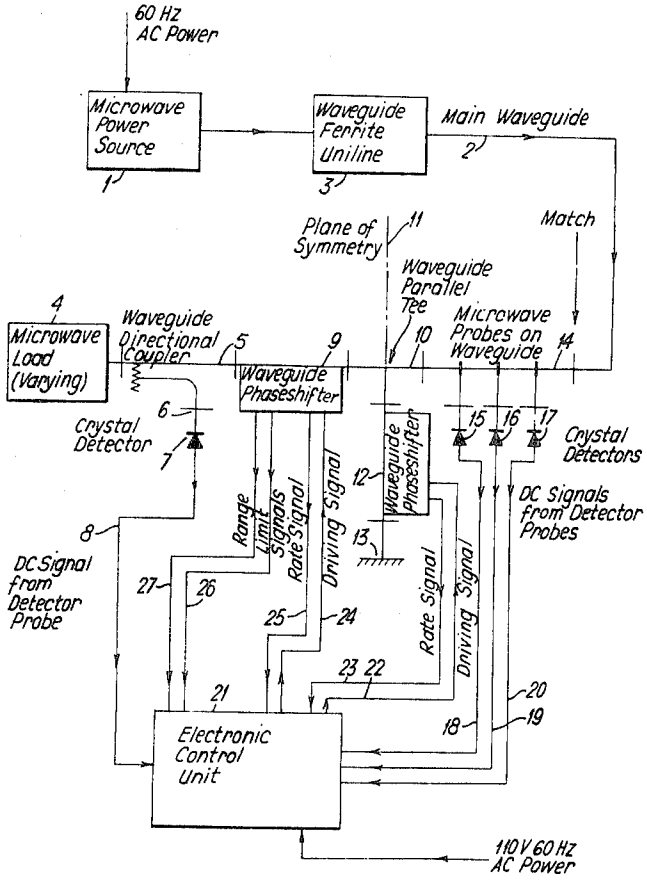
2,832,934	4/1958	Walters	333/17

FOREIGN PATENTS

545,019	8/1957	Canada	333/17

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ABSTRACT: An impedance matching device for automatically and continuously matching a time varying microwave load to a fixed frequency microwave power source and its output line.



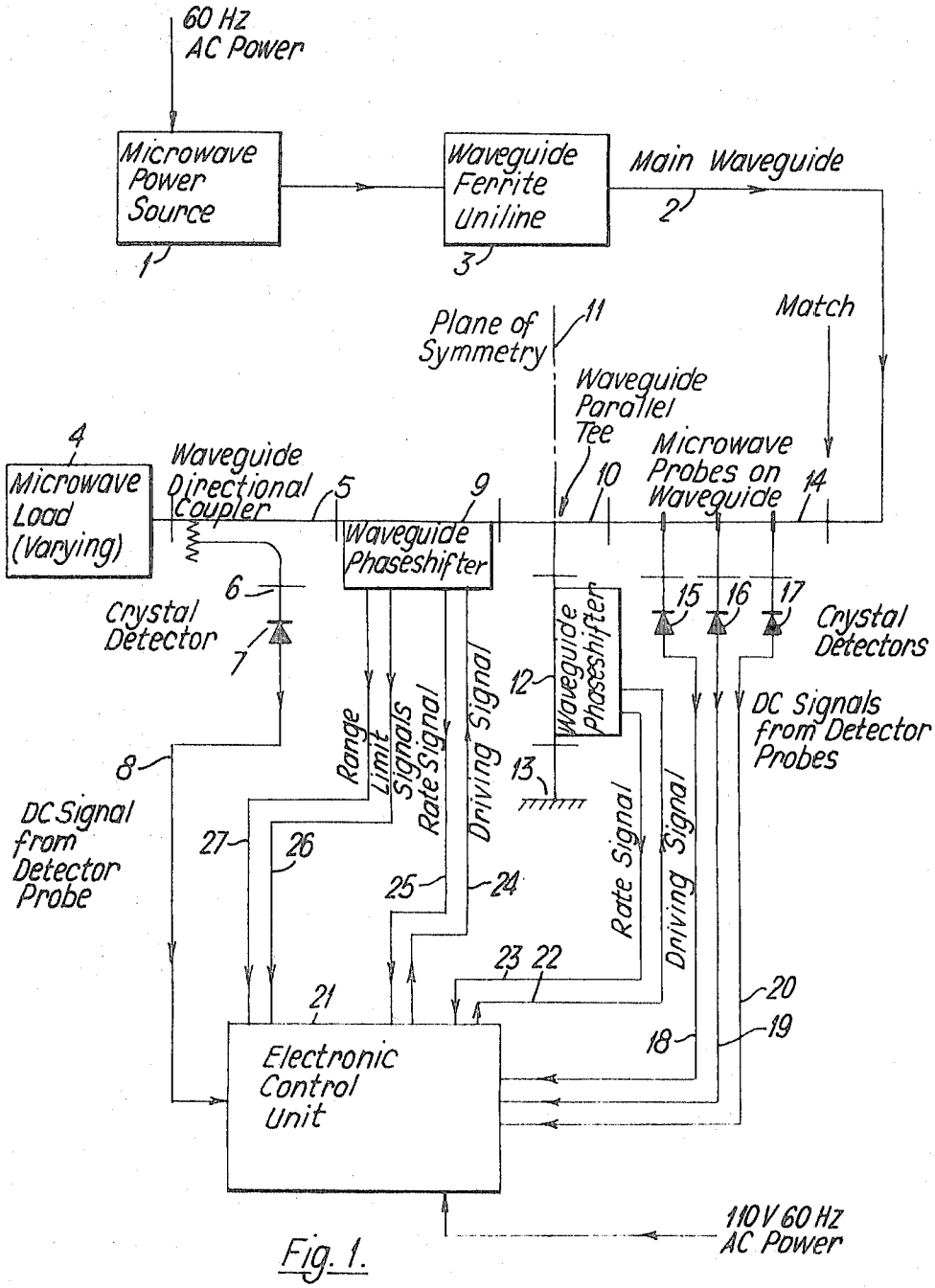


Fig. 1.

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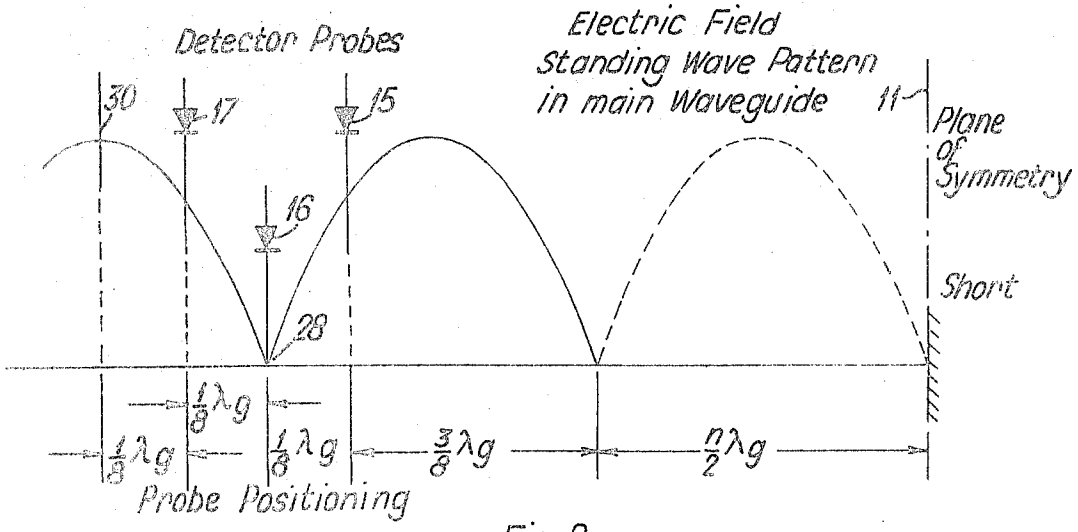


Fig. 2.

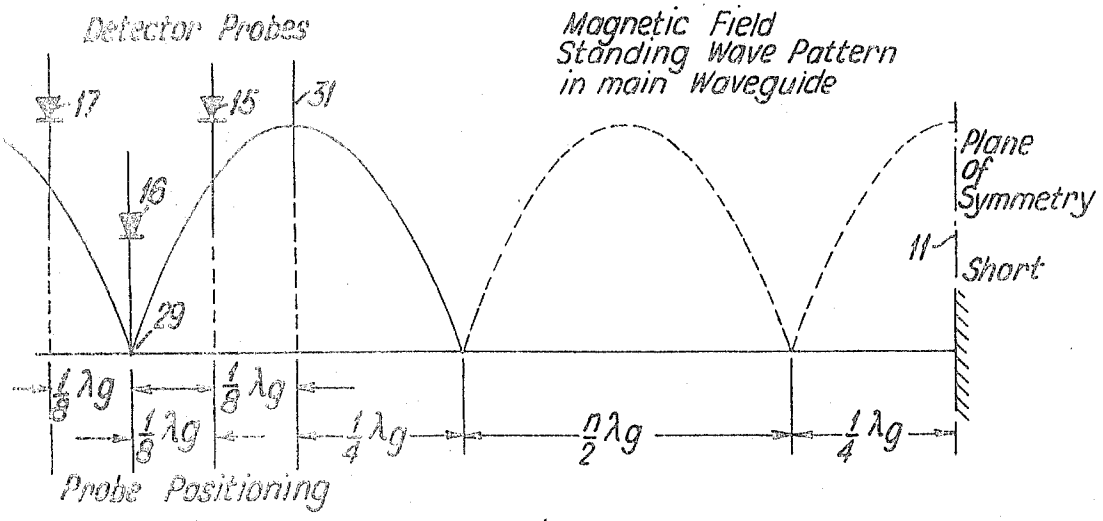


Fig. 3.

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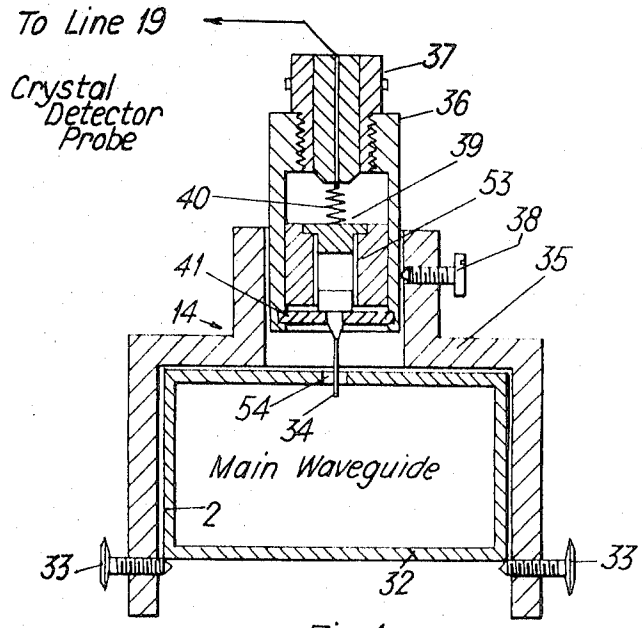


Fig.4.

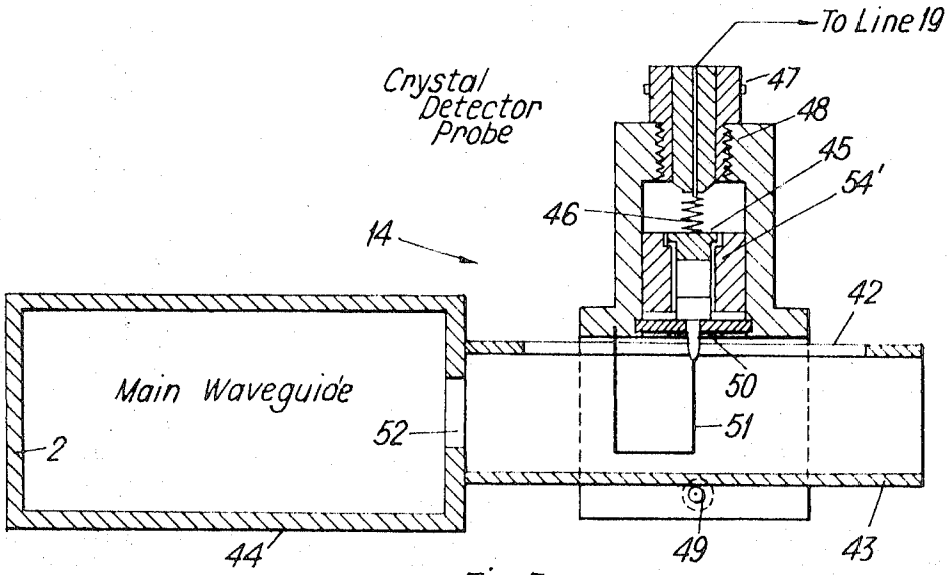


Fig.5.

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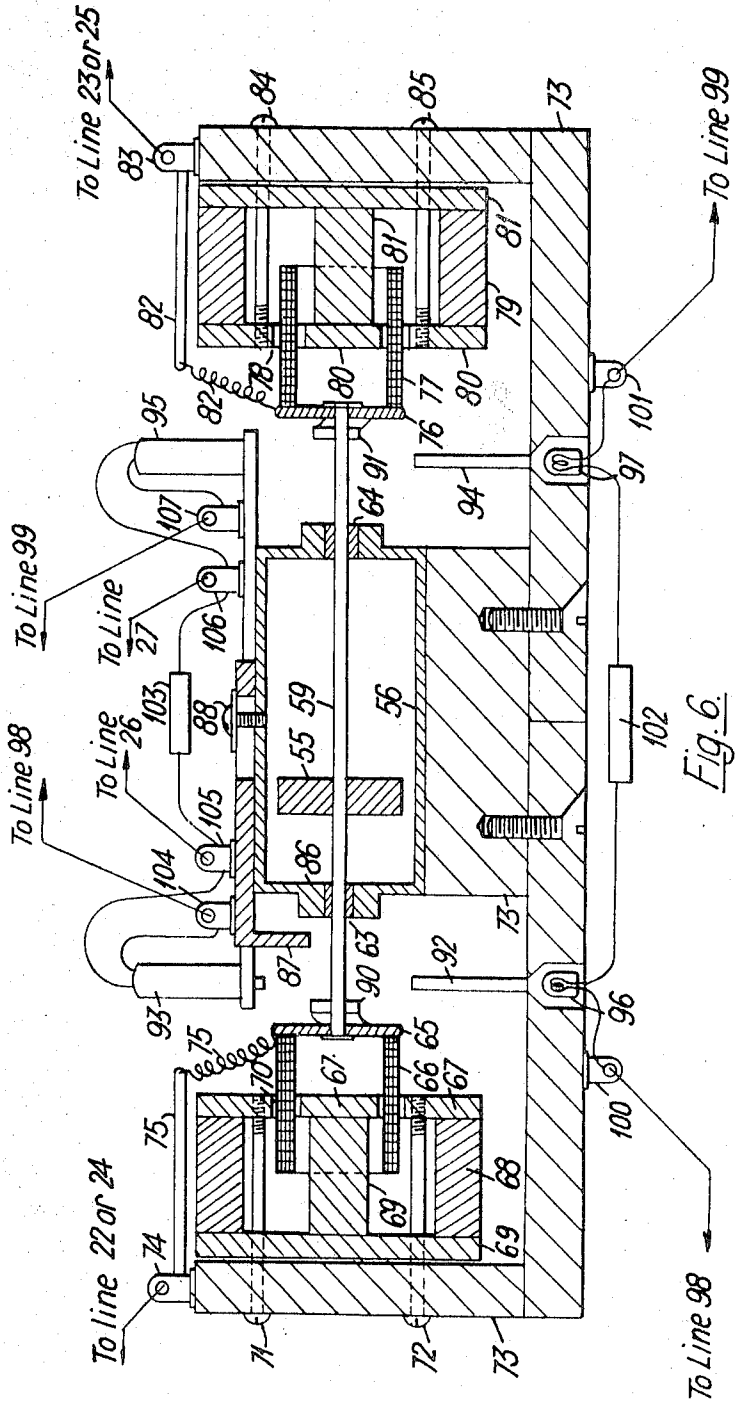


Fig. 6.

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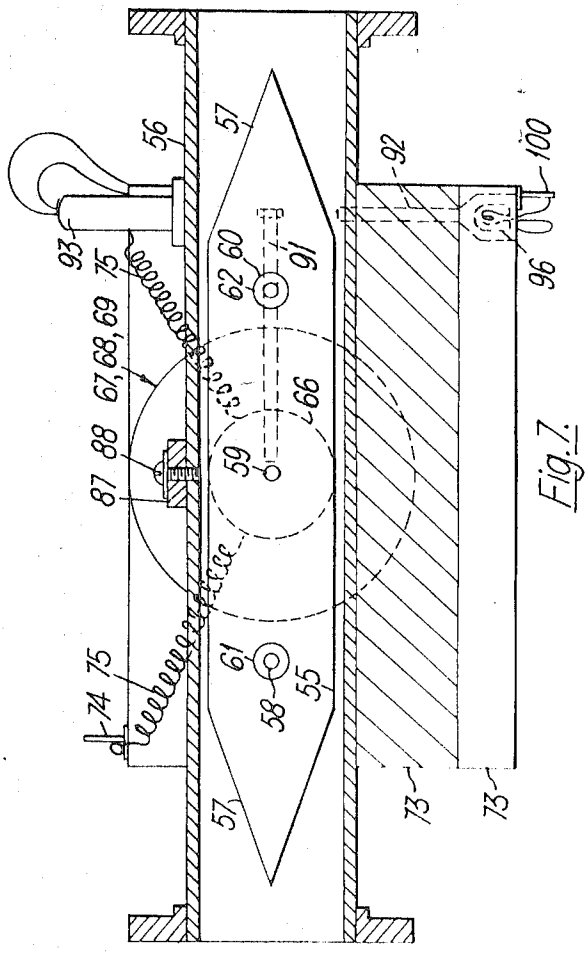


Fig. 7.

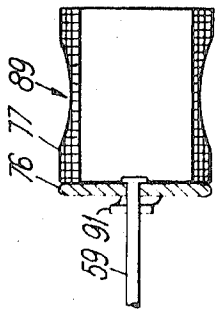


Fig. 8.

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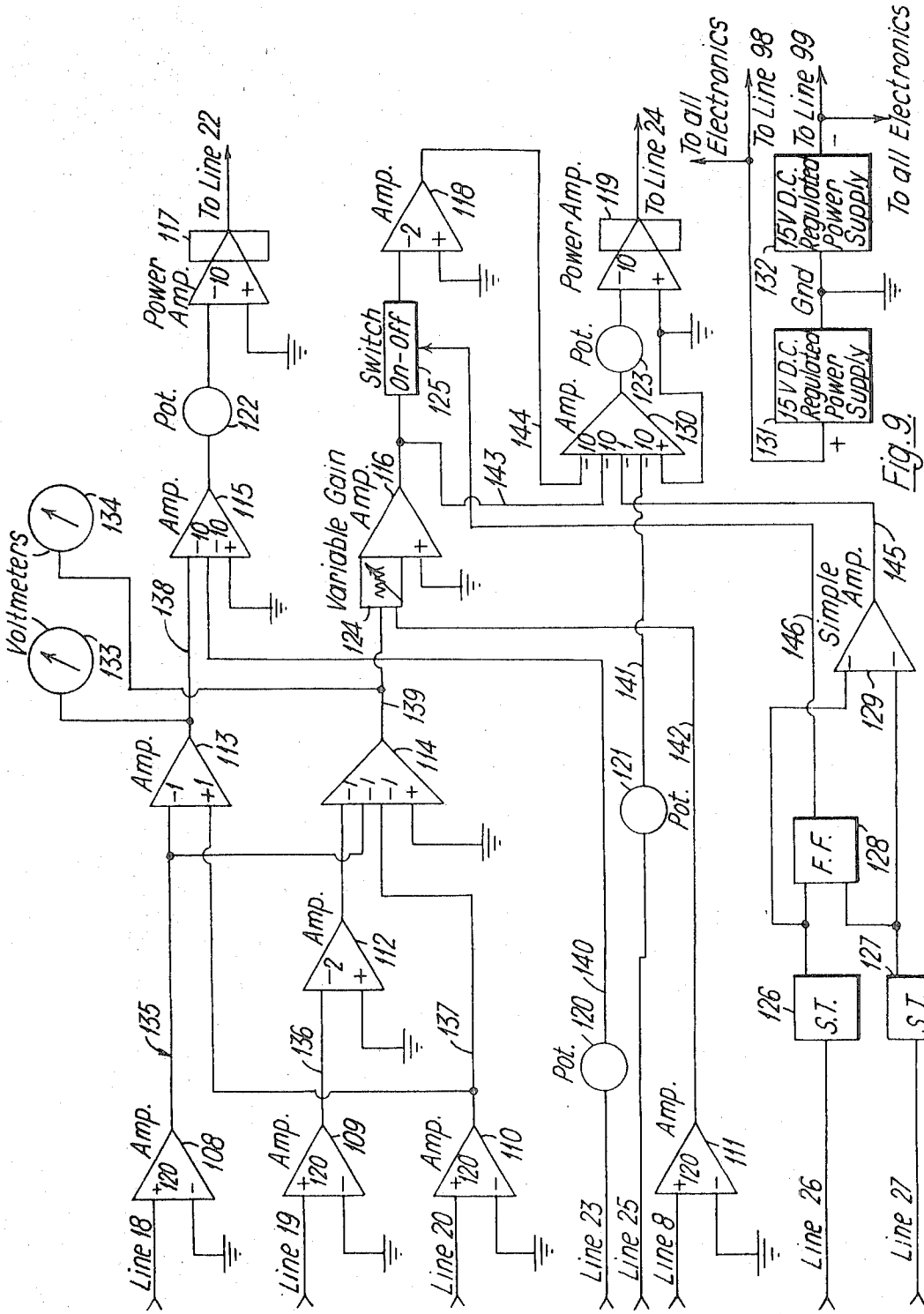


Fig. 9

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MICROWAVE IMPEDANCE MATCHING SYSTEM

This invention relates to a microwave impedance matching system for matching a microwave input waveguide to a microwave output waveguide.

In microwave systems, it is important that one section of a waveguide be matched to another section and this is particularly true when the other section is the output section having a microwave load connected thereto. Microwave power sources such as power klystrons, magnetrons, and similar devices are commonly used to deliver microwave energy to radiating apparatus, to cavities for heating of materials, to meander lines for drying sheet or filmlike materials, and to similar devices in which electromagnetic fields at microwave frequencies have to be developed. Commonly, these loading devices present admittances to the microwave power source and its output line that do not constitute matched conditions. Moreover, the admittances of the loading devices often vary with time as a result of changes in the physical properties of the devices themselves, or the materials contained within them.

Frequently, microwave power sources operate properly only if the degree of mismatch between the load and the power source with its output line does not exceed certain limits. In fact, damage to the power source may result if large degrees of mismatch are allowed to exist for some period of time. As is well known, microwave power sources reach their greatest efficiency and deliver their maximum power to the load only if the load is matched to the power source and its output line.

In view of the above, it is of the utmost importance that a matched condition be maintained between the microwave power source and its load and that, in the event of a change in the loading, a correction be applied as rapidly as possible to return the source and load to matched conditions. Maintenance of matched conditions at all times should produce considerable benefits resulting from high efficiency, and increased life and reliability of operation of the power sources.

Previously proposed methods of dealing with fixed mismatch conditions are the inserting of matching devices in the waveguide or line connecting the power source and its load, such as slide-screw tuners, E-H tuners, single and double stub tuners, and sets of adjusting rods or screws protruding into the waveguide. A matched condition is normally obtained by adjustment of one or more of the above devices.

Loads that vary with the passage of time are often dealt with by means of a special construction of the loading device or by repeated adjustment of matching devices by a human operator. Under these circumstances only very approximate matching can be obtained.

It is an object of the present invention to provide a microwave impedance matching system which is capable of use to sense the degree of mismatch or match between a microwave input waveguide and a microwave output waveguide and to provide automatic adjustment whereby said input and output waveguides are maintained in a substantially matched condition.

According to the present invention, there is provided a microwave impedance matching system for matching a microwave input waveguide to a microwave output waveguide including a waveguide parallel tee connected to the output waveguide, said parallel tee including a parallel short circuit, a mismatch sensing device associated with the input waveguide to sample the standing wave pattern therein and to provide signals indicative of the degree of mismatch of said input waveguide to said output waveguide, a first waveguide phase-shifting device connected in said parallel tee between said input waveguide and said short circuit, a second waveguide phase-shifting device connected in said output waveguide, said first and second waveguide phase-shifting devices being capable of adjustment in response to said signals to change the value of admittance at the plane of symmetry of said waveguide parallel tee in a direction to reduce the degree of mismatch of said input waveguide to said output waveguide.

An embodiment of the present invention will now be described, by way of example, with reference to the accompanying drawings in which:

FIG. 1 is a diagrammatic representation, in block form, of apparatus according to the present invention;

FIG. 2 is a graphical representation of the electric field standing wave pattern in the main waveguide of FIG. 1 to illustrate the positioning of the detector probes therein;

FIG. 3 is a graphical representation of the magnetic field standing wave pattern in the main waveguide of FIG. 1 to illustrate the positioning of the detector probes therein;

FIG. 4 is a diagrammatic representation, partly in cross section, of a crystal detector probe for use in the apparatus of FIG. 1 to sample the electric field in the main waveguide;

FIG. 5 is a diagrammatic representation, partly in cross section, of a typical detector probe for use in the apparatus of FIG. 1 to sample the magnetic field intensity in the main waveguide;

FIG. 6 diagrammatically illustrates a typical phase-shifter device, partly in cross section, for use in the apparatus of FIG. 1;

FIG. 7 is a diagrammatic representation, partly in cross section, of a part of the phase-shifter of FIG. 6, the view being taken at right angles to the view illustrated in FIG. 6 and substantially parallel to the longitudinal axis of the respective waveguide section;

FIG. 8 is a cross-sectional representation to show the construction of a drive coil for use in that phase-shifter which is located in the waveguide parallel tee of FIG. 1; and

FIG. 9 is a block schematic representation of the electronic control unit which it utilized in the apparatus illustrated in FIG. 1.

Throughout the drawings the same numbers are used to illustrate like parts.

Referring to FIG. 1, microwave energy from a microwave power source 1 is fed to a main waveguide 2, by way of a ferrite uniline stage 3. The uniline stage 3 is effective to match the power source 1 to the main waveguide 2 by allowing energy to pass unattenuated only in the direction from power source 1 to main waveguide 2. Reflected energy moving in the direction from main waveguide 2 towards the power source 1 is absorbed in the ferrite uniline 3. The illustrated arrangement of the microwave power source and the uniline stage is conventional.

Energy emerging from uniline stage 3 is transmitted through the main waveguide 2, i.e. the input waveguide, and delivered to the microwave waveguide load 4 by way of the output waveguide, of which it may be regarded as forming a part. If the waveguide load 4 were matched to the main waveguide 2, i.e. if the admittance presented by waveguide load 4 were equal to the characteristic admittance of main waveguide 2, all the energy delivered by main waveguide 2 to the load 4 would be absorbed in waveguide load 4 and none of the energy would be reflected. However, if waveguide load 4 is not matched to main waveguide 2, some of the energy delivered to load 4 by waveguide 2 will be reflected by load 4. A small portion of the energy reflected by waveguide load 4 emerges from port 6 of waveguide directional coupler 5. Crystal detector 7, which is made to operate in its square law region, converts the microwave energy emerging from the port into a DC signal on line 8. Because of the particular and conventional mode of operation of directional coupler 5 and detector crystal 7, line 8 carries a DC signal which is proportional to the square of the reflection coefficient of microwave waveguide load 4. The use of the signal on line 8 will be discussed later.

Admittance is a complex quantity which can be considered as consisting of a real part and an imaginary part. Waveguide short circuit 13, together with phase-shifter 12, is capable of producing any desired positive or negative imaginary admittance in parallel with main waveguide 2 at the plane of symmetry 11 of waveguide parallel tee 10. The actual value of this admittance depends upon the adjustment of phase-shifter 12. Phase-shifter 9, it its adjustment is altered, changes the

electrical line length between microwave waveguide load 4 and the plane of symmetry 11 of waveguide parallel tee 10. The total admittance in main waveguide 2 at the plane of symmetry 11 of parallel tee 10 is determined by the admittance of waveguide load 4 as altered through the particular electrical line length which depends upon the adjustment of phase-shifter 9, and by the imaginary admittance added by waveguide short 13 and phase-shifter 12.

The total waveguide load, i.e. the output waveguide, comprising microwave load 4, waveguide directional coupler 5, line-length phase-shifter 9, waveguide parallel tee 10, parallel stub phase-shifter 12, and waveguide short 13, may be matched to main waveguide 2, i.e. the input waveguide, by first adjusting phase-shifter 9 until the real part of the admittance at the plane of symmetry 11 is equal to the admittance of main waveguide 2 and by, thereafter, adjusting phase-shifter 12 to produce enough parallel imaginary admittance of appropriate sign to cancel the imaginary part of the admittance at the plane of symmetry 11.

If the total admittance at the plane of symmetry 11 of parallel tee 10 is equal to the admittance of the main waveguide 2, the load is matched and there will be no reflection of energy from the plane of symmetry 11 in the main waveguide 2. If the total admittance at the plane of symmetry 11 is not equal to the admittance of the main waveguide 2, some of the energy transmitted towards the load by main waveguide 2 will be reflected. The energy travelling towards the plane of symmetry 11 and the energy reflected back from the plane of symmetry 11 will interfere and set up a standing wave pattern in the main waveguide 2.

Microwave probes 14 on the input main waveguide 2 sample the particular standing wave pattern that exists. A small portion of the energy travelling in both directions along the main waveguide 2 reaches crystal detectors 15, 16 and 17. Crystal detectors 15, 16 and 17 are especially positioned along the main waveguide 2, and the penetration of the microwave probe 14 is adjusted such that crystal detectors 15, 16 and 17 operate in their square law regions. More particularly, the positioning and adjustment of penetration into the waveguide of probes 14 is such that the resulting DC signals on lines 18, 19 and 20 can be arithmetically combined in the electronic control unit 21 to produce electrical signals proportional to the real and imaginary vector components of the reflection coefficient at the plane of symmetry 11 of parallel tee 10.

The signal proportional to the imaginary vector component of the reflection coefficient at the plane of symmetry 11 is amplified many times and is then applied, through line 22, to an electromechanical mechanism which adjusts phase-shifter 12. This constitutes a closed negative feedback loop. The adjustable part of phase-shifter 12 will continue to move until the imaginary vector component of the reflection coefficient at the plane of symmetry 11 has become zero. While the adjustable portion of phase-shifter 12 moves, the electromechanical driving mechanism will also produce an electrical signal whose magnitude depends on the rate and direction of motion and upon the instantaneous position of the adjustable part of phase-shifter 12. The said rate signal appears on line 23. Electronic control unit 21 amplifies the rate signal on line 23 and mixes it with the signal proportional to the imaginary vector component of the reflection coefficient at the plane of symmetry 11. The rate signal of line 23, therefore, serves to damp the motion of the adjustable part of phase-shifter 12, and to prevent the adjustable part of phase-shifter 12 from moving too far by braking its motion.

The said damping produce by the rate signal on line 23 is purposely made nonlinear, by having it depend upon the position of the adjustable portion of phase-shifter 12. This is done in order to obtain minimum time adjustment of phase-shifter 12 for all degrees of mismatch of waveguide load 4. The effective loop gain of the control loop involving phase-shifter 12 grows to infinity at extreme positions of the adjustable part of phase-shifter 12. As explained later, the range of adjustment of phase-shifter 12 has been mechanically limited, so that the loop gain merely becomes very large. The rate signal is made to increase as the adjustable part of phase-shifter 12 approaches extreme positions in order to maintain optimum damping over the full range of adjustment of phase-shifter 12 independent of the effective loop gain.

The range of adjustment of phase-shifter 12 is mechanically limited to slightly less than 180° of phase-shift in such a way that the position corresponding to zero imaginary admittance added at the plane of symmetry 11 on main waveguide 2 lies in the center of the adjustment range of phase-shifter 12. Within this limited range each position of adjustment of phase-shifter 12 corresponds to a unique value of imaginary admittance which appears in parallel with main waveguide 2 at the plane of symmetry 11 of parallel tee 10.

The signal proportional to the real vector component of the reflection coefficient at the plane of symmetry 11 is greatly amplified and then applied to the electromechanical driving mechanism of phase-shifter 9 along line 24, in order to move the adjustable part of phase-shifter 9. While the adjustable portion of phase-shifter 9 is moving, its electromechanical driving mechanism also produces a rate signal along line 25 which depends upon the rate and direction of motion of the adjustable part of phase-shifter 9. In the electronic control unit 21 the rate signal of line 25 is amplified and mixed with the real vector component signal of the reflection coefficient at the plane of symmetry 11. Thus, the rate signal on line 25 serves to damp the motion of the adjustable part of phase-shifter 9, to brake it and prevent motion beyond the point of balance. Once again, the above constitutes a closed negative feedback control loop; the adjustable portion of phase-shifter 9 continues to move until the real vector component of the reflection coefficient at the plane of symmetry 11 has become zero.

The effective loop gain of the control loop involving phase-shifter 9 depends, to a large extent, upon the magnitude of the reflection coefficient of waveguide load 4. In order to obtain minimum time adjustment of phase-shifter 9 for a large range of load 4 values, it is necessary to change the control loop gain in accordance with the magnitude of the reflection coefficient of waveguide load 4. Electronic control unit 21 contains a means of changing the gain of the control loop involving phase-shifter 9 as a function of the signal of line 8 which is proportional to the square of the reflection coefficient of waveguide load 4.

The position of balance of the adjustable part of phase-shifter 9, corresponding to a certain value of waveguide load 4, is not unique. Within any particular 180° range of adjustment of phase-shifter 9, there are two distinct positions of balance, of which one is a stable balance point while the other point is unstable. Whichever of the two balance points is stable depends upon the load 4 and upon the sign of the loop gain involving phase-shifter 9. Certain cyclical changes in the value of waveguide load 4 could force phase-shifter 9 to try and increase its phase-shift well beyond the range of 180° to which it is mechanically limited. Should phase-shifter 9, in the course of trying to reach and maintain a balance, want to exceed one of its limits of adjustment, an electro-optical device will sense this and will produce an electrical voltage on either one of these lines 26 and 27. Electronic control unit 21 reacts to these signals on lines 26 and 27 by changing the sign of the gain of the control loop involving phase-shifter 9, and by simultaneously producing a short pulse on line 24 which drives phase-shifter 9 away from its limit of adjustment. Switching the sign of the control loop gain changes the previously stable balance point to an unstable one and causes phase-shifter 9 to seek out the formerly unstable, but now stable, balance point which will assuredly lie within its range of adjustment. Driving phase-shifter 9 away from the particular limit of adjustment towards the new balance point by means of a pulse of suitable length and polarity on line 24 assures that the adjustment towards the new balance is initiated in the correct direction and that the adjustment will be completed in minimum time.

The two separate control loops mentioned above operate simultaneously and continuously, but not, by any means, independently. The automatic matching of a load, which has just deviated from a previous value, by the action of the two control loops upon the moving parts of the phase-shifters 9 and 12, proceeds according to a definite but variable schedule which is a function of the new value of load 4 and the previous adjustment positions of the phase-shifters 9 and 12. The schedule of motion of the adjustable parts of phase-shifters 9 and 12 will be such that minimum time is consumed in the adjustment.

FIGS. 2 and 3 illustrate the proper positioning of the crystal detector probes 14 along the main waveguide 2.

There are two distinct cases. For low power systems probes 14 may be used which sample the intensity of the electric field in the main waveguide 2. Electric field sampling is depicted in FIG. 2.

At high microwave power levels problems may arise with waveguide arcing and breakdown if electric field probes are used. Therefore, at high power levels the magnetic field intensity is sampled instead, by means of differently arranged probes 14. Magnetic field sampling is shown in FIG. 3.

Referring first to electric field sampling, as shown in FIG. 2, if the main waveguide 2 is terminated with a fictitious short at the plane of symmetry 11 of parallel tee 10, minimal in the electric field will occur along main waveguide 2 at points $n/2$ λg distance away from the short, when n is a positive integer and λg is the wavelength in the waveguide. Central crystal detector probe 16 is then positioned such that it samples the electric field exactly at such a minimum 28. Crystal detector probes 15 and 17 are, thereafter, positioned one on either side of central probe 16 and 1/8 λg away from the central probe 16.

Now referring to magnetic field sampling as shown in FIG. 3, for the same fictitious short as above at the plane of symmetry 11 of parallel tee 10, minimal in magnetic field intensity will occur at points ($n/2$ λg + 1/4 λg) distance away from the short, where n is a zero or positive integer and λg is the waveguide wavelength. Again, central probe 16 is placed exactly at a minimum 29 in magnetic field intensity resulting from a short at the plane of symmetry 11, while crystal detector probes 15 and 17 are placed on either side of probe 16 but 1/8 λg away from probe 16.

FIGS. 2 and 3 have several requirements in common. The microwave crystals used for crystal detector probes 15, 16 and 17, preferably, should be matched. A further requirement is that for a matched load condition the outputs from crystal detectors 15, 16 and 17 be equal, while the amplitude should be such that the detector crystals 15, 16 and 17 always operate in their square law regions for the power levels used and for almost all degrees of mismatch. The detector probe section 14 contains means of adjusting the actual intensity of the electric or magnetic field reaching the detector crystals. To obtain the proper operation of probe section 14, the field intensity at detector crystal 17 is first adjusted such that crystal 17 will deliver maximum DC signal while still operating in its square law region. Then, with the entire matching apparatus in working order, the field intensity at detector crystals 15 and 16 is adjusted to obtain a matched load condition.

An alternate method of obtaining the correct setting of the field intensity at the probe crystals 15, 16 and 17 is to connect a matched load to main waveguide 2 directly after the detector probe section 14. The field intensity at detector 17 is, again, adjusted for operation of the crystal well within its square law region. The field intensities at detector crystals 15 and 16 are subsequently set such that their DC output signals are equal to that of crystals 17.

Introduction of detector crystal probes 15, 16 and 17 into main waveguide 2 will produce some undesirable reflections in main waveguide 2. However, most of these reflections can be cancelled out. Crystal probes 15 and 17 are placed one quarter wavelength apart; their reflections in main waveguide 2, therefore, cancel. The reflection caused by detector probe 16 can be cancelled by placing a dummy probe without a crystal, 30 or 31, one quarter guide wavelength away from detector probe 16. Under these conditions, probe section 14 will have minimum effect upon the standing wave pattern in main waveguide 2.

FIG. 4 represents a cross section of one of the crystal detector probes of probe section 14 used to sample the electric field. The electric field to be sampled appears in waveguide section 32 which is part of main waveguide 2. Movable holder 35 can be slid along waveguide section 32 for positioning of the crystal probes, while setscrews 33 will fasten holder 36 in a fixed position. The electric field is sampled by probe 34 which is connected to one terminal of detector crystal 39. Probe 34 is also connected to the metal parts of detector body 36, which serves as ground connection, through disc resistor 41. Disc resistor 41 is necessary to provide a return path for the DC output signal from crystal 39 which passes to BNC connector 37 through contact and retaining spring 40. Output line 19 connects to BNC connector 37 and consists of a shielded cable. The center conductor of shielded cable 19 carries the signal from crystal 39 while its outer conductor is tied to the grounded metal parts of detector body 36. Coupling slot 54 allows probe 34 to protrude into the waveguide section 32. As explained previously, the degree of electrical coupling between the electric field in waveguide section 32 and probe 34, and therefore the electric field intensity reaching crystal 39 needs to be varied. This is accomplished by raising or lowering of detector body 36 in holder 35 and by then fixing probe 34 at the desired penetration by tightening of setscrew 38.

A method for sampling of the magnetic field intensity in main waveguide 2 at high microwave power levels is illustrated in FIG. 5. Waveguide section 44 is part of main waveguide 2 which carries the high power microwave signal. A small part of the magnetic field in waveguide section 44 is coupled into auxiliary waveguide 43 by means of round coupling hole 52. Auxiliary waveguide 43 has dimensions that are considerable smaller than those of waveguide section 44, which means that auxiliary waveguide 43 operates in a cutoff mode. A waveguide operating in a cutoff mode will not propagate energy; instead, the electric and magnetic fields in cutoff waveguide 43 decay exponentially with increasing distance away from coupling hole 52. Coupling loop 51 samples the magnetic field in auxiliary waveguide 43. One side of coupling loop 51 is grounded to crystal detector body 48, while the other side is connected to one terminal of detector crystal 45 which is insulated from the grounded metal parts of detector body 48 and from the metal waveguide 43 by means of plastic insert 54' and insulator disc 50. The intensity of the magnetic field coupling into crystal 45 may thus be adjusted by varying the position of coupling loop 51 along auxiliary waveguide 43. The output signal from crystal 45 passes through contact and retaining spring 46 to the inner conductor terminal of BNC connector 47. Line 19 is, again, a coaxial cable, the inner conductor of which carries the DC output signal from crystal 45, while its outer conductor is grounded to the metal parts of detector body 48 by means of connector 47. Auxiliary waveguide 43 contains a central longitudinal slot 42 which allows room for coupling loop 51 if detector body 48 is slid along waveguide 43 to vary the intensity of the sampled magnetic field. Detector body 48 can be fixed in position on auxiliary waveguide 43 by means of setscrew 49.

The electromechanical phase-shifters 9 and 12 in FIG. 1 are similar in construction. A representative phase-shifter is illustrated in FIGS. 6 and 7. The operation and construction of the typical phase-shifter shown in FIGS. 6 and 7 will first be explained; later, the differences between phase-shifters 9 and 12 will be set forth.

The phase-shifter illustrated is of the movable dielectric slab type. Dielectric slab 55 contained within waveguide section 56 can be moved transversely in waveguide section 56 to produce varying amounts of differential phase-shift.

Polystyrene is a reasonably rigid plastic which absorbs very little power at microwave frequencies. Polystyrene has, therefore, been chosen as the material for construction of dielectric slab **55**. In order to reduce the occurrence of troublesome microwave reflections the dielectric slab **55** has long tapers **57** at either end. The slab **55** is supported in waveguide section **56** on three hollow, brass, rhodium plated, and highly polished pins **58**, **59** and **60**. Central pin **59** slides in two Teflon sleeve bearings **63** and **64** and has slab **55** solidly attached to it. Moving of pin **59** in its sleeve bearings **63** and **64** causes a change in position of slab **55** in waveguide section **56**. It is necessary to cancel reflections of microwave energy from pin **59** over a broad range of microwave frequencies, and it is equally essential to prevent slab **55** from rotating about pin **59**. Therefore, pins **58** and **60** were added at distances of three-eighth of a guide wavelength away from pin **59**. Slab **55** slides on pins **58** and **60** which are rigidly attached to the sidewalls of waveguide section **56**, by means of Teflon inserts **61** and **62**. Teflon is used for the support bearing surfaces since polished rhodium sliding on Teflon produces a very low friction bearing. Teflon is also a material which exhibits very low loss properties in microwave fields, and it has a dielectric constant which is very close to that of polystyrene.

Waveguide section **56** is attached to a support structure **73** which simultaneously serves to support two magnet structures which consist of permanent magnets **68** and **79**, yokes **69** and **81**, and polepieces **67** and **80**. Yokes **69** and **81**, and polepieces **67** and **80** are shaped such that most of the magnetic field induced by permanent magnets **68** and **79** appears in magnetic airgaps **70** and **78** respectively. The magnet structures are fastened to the support **73** by means of screws **71**, **72**, **84** and **85**.

Attached to either end of pin **59** there are two plastic discs **65** and **76** which, respectively, support two enamel insulated, copper wire coils **66** and **77**. Coils **66** and **77** move in air gaps **70** and **78** simultaneously as slab **55** and pin **59** move. Thin electrical wires **75** connect coil **66** to terminals **74** and thin wires **82** connect coil **77** to terminals **83**. Coil **66** is the drive coil which will cause slab **55** to move in waveguide section **56**. Application of a voltage to terminals **74** causes a current to flow in coil **66** which, in turn, produces a force on coil **66** since part of coil **66** is contained within magnetic airgap **70**. The force produced is a function of the current magnitude and direction in coil **66**, but does not depend on the position of slab **55** in waveguide section **56** since a fixed number of turns of coil **66** is always contained within magnetic airgap **70**.

It is, thus, a feature of the illustrated construction of this phase-shifter that a current in coil **66**, resulting from a voltage applied to terminals **74**, is directly converted into a proportional force which causes linear transverse motion of slab **55** in waveguide section **56**, while the frictional resistance to motion of slab **55** is minimal.

Motion of slab **55** and pin **59** is accompanied by similar motion of coil **77** in magnetic airgap **78**. Coil **77** in gap **78** operates in a manner reciprocal to that of coil **66**. Coil **77** produces a voltage at terminals **83** which is directly proportional to the velocity or rate of motion of slab **55**. The output voltage at terminal **83** is, therefore, called the rate signal.

Over a limited range of motion of slab **55** close to sidewall **86** in waveguide section **56**, the differential phase-shift produced by this phase-shifter is almost linearly related to the position of slab **55** with respect to sidewall **86**. Slab **55** is allowed to move over such a range that at one extreme slab **55** contacts sidewall **86**, while at the other extreme position disc **65** contacts brackets **87**. The position of bracket **87** is adjustable. Moreover, bracket **87** can be fixed, by means of screw **88**, in such a position that the total range of differential phase-shift is 180°.

Now referring specifically to the construction of linelength phase-shifter **9**, as illustrated in FIGS. **6** and **7**, some special additional features become apparent.

Drive coil **66**, as part of phase-shifter **9**, consists of two full-length layers of enamel insulated copper wire cemented into a cylindrical coil shape. Likewise, rate coil **77** consists of six layers of thin enamel insulated wire cemented into a cylindrical shape.

The total range of differential phase-shift of phase-shifter **9** is set to slightly more than 180° by means of bracket **87**. Discs **65** and **76** have two vanes **90** and **91**, respectively, which, at the extreme positions of slab **55** in waveguide section **56**, interrupt light beams which pass from light source tube **92** to photocell **93** and from light source tube **94** to photocell **95**. Light source tubes **92** and **94** are hollow brass tubes which direct the light from wheat grain bulbs **96** and **97** in narrow beams towards photocells **93** and **95** which, in turn, are allowed to have only a narrow angle of light acceptance. Voltage is applied across terminals **100** and **101** and, therefore, across the series connection of light bulb **96**, resistor **102** and light bulb **97**, where resistor **102** sets the proper operating current for light bulbs **96** and **97**. Photocell **93**, resistor **103** and photocell **95** are connected in series between terminals **104** and **107**, while the same voltage is applied between terminals **104** and **107** as between terminals **100** and **101**. Resistor **103** sets the operating current for photocells **93** and **95**.

Normally, with light reaching both of photocells **93** and **95**, the effective resistance of photocells **93** and **95** is low and almost no voltage appears between terminals **104** and **105** on the one hand, and terminals **106** and **107** on the other. If slab **55** reaches one of its two extreme positions the light to one of photocells **93** and **95** will be interrupted. The photocell in question will increase its resistance and a voltage will suddenly appear between either terminals **104** and **105**, or terminals **106** and **107**. Electronic control unit **21** reacts to the appearance of voltage on either one of lines **26** and **27**, which are connected to terminals **105** and **106** respectively.

Shorted stub phase-shifter **12** is similar in construction to phase-shifter **9**, but with some important differences which are described here.

The range of differential phase-shift of phase-shifter **12** is made to be slightly less than 180°, by means of bracket **87**.

Since no corrective action needs to be taken if slab **55** of phase-shifter **12** reaches either extreme position, the entire light source and photocell structure is missing. Specifically, phase-shifter **12** does not have light bulbs **92** and **94**, photocells **93** and **95**, resistors **102** and **103**, vanes **90** and **91**, nor any of the connection terminals **100**, **101**, **104**, **105**, **106** and **107** associated with them.

The construction of drive coil **66** of phase-shifter **12** is exactly the same as that of phase-shifter **9**. However, rate coil **77** of phase-shifter **12** is different. Referring to FIG. **8**, rate coil **77** is wound with eight layers of fine enamel insulated copper wire cemented into the cylindrical shape. But, the various layers do not all extend over the full length of the coil. The first layer extends over the full length, while each successive layer has an ever widening central gap. The overall result is that, in cross section the coil exhibits a curved profile **89** which approximates a secant squared curve. The rate signal produced by coil **77** of phase-shifter **12** is now a function of both the slab **55** velocity and its position in waveguide section **56**. An explanation of the need for this was presented before.

FIG. **9** is a diagram which shows the construction of electronic control unit **21** in a little more detail.

As shown in FIG. **9**, the signals from crystal detectors **15**, **16** and **17** which arrive along lines **18**, **19** and **20** are immediately amplified by amplifiers **108**, **109** and **110**. Amplifiers **108**, **109** and **110** have exactly equal gains so that the ratios of the signals after amplification are not altered. The said three amplifiers are integrated circuit operational amplifiers used in a positive gain mode and with their input impedances set such that detector crystals **15**, **16** and **17** will most closely approach square law operation, while high initial gain reduces noise problems.

After the initial amplification the signals which now appear on lines **135**, **136** and **137** are combined as follows: operational amplifier **113**, used in a unity gain differential mode, produces an output on line **138** which is equal to the dif-

ference between the signals on lines 135 and 137; the signal on line 138 is, in fact, proportional to the imaginary vector component of the reflection coefficient at plane of symmetry 11 in main waveguide 2. The sign and magnitude of the signal on line 138 are displayed on meter 133. Similarly, integrated circuit operational amplifier 114 sums the signals on lines 135 and 137 and adds to this the output from operational amplifier 112 whose output is equal to two times the signal on line 136. The resulting output signal from amplifier 114 which appears on line 139 is proportional to the real vector component of the reflection coefficient at the plane of symmetry 11 in main waveguide 2. Again, the sign and magnitude of the signal on line 139 can be read off meter 134.

The rate signal of line 23 passes through potentiometer 120 which allows the damping of the control loop to be adjusted, and then appears on line 140. Integrated operational amplifier 115 further amplifies the sum of the signal on lines 138 and 140. The output from amplifier 115 is fed to power amplifier 117 through potentiometer 122 which makes it possible to set the control loop gain. Power amplifier 117 adds further voltage gain and has high output current capabilities. Line 22 connects the output from power amplifier 117 to the drive coil of the shorted stub phase-shifter 12.

Line 25 carries the series line phase-shifter 9 rate signal which is adjusted in magnitude by potentiometer 121 and which then appears on line 141. Potentiometer 121 is another control loop damping adjustment element.

The signal on line 8, which is proportional to the square of the load 4 reflection coefficient, is amplified by integrated circuit operational amplifier 111 and delivered to line 142.

Whenever slab 55 of series line phase-shifter 9 reaches an extreme in position, a signal will appear on line 26 or 27. Transistor Schmitt triggers 126 ans 127 react to these signals by producing outputs. Schmitt trigger 126 is connected to positive supply voltage, while Schmitt trigger 127 is supplied from the negative power supply. Schmitt trigger 126, therefore, produces a positive output whenever a signal of sufficient magnitude appears on line 26, and Schmitt trigger 127 puts out a negative voltage if a sufficiently large signal appears on line 27. Schmitt triggers 126 and 127 will never produce simultaneous outputs. The outputs from Schmitt triggers 126 and 127 are fed to a simple two transistor amplifier which clips and combines the outputs from the Schmitt triggers into one signal on line 145. The output of amplifier 129 on line 145 is normally zero, but whenever a photocell light beam is interrupted in phase-shifter 9 as a result of slab 55 approaching an extreme position a positive or negative fixed amplitude signal will appear on line 145 which lasts as long as the light beam remains interrupted. Whether the signal on line 145 is positive or negative depends on which one of the two light beams on phase-shifter 9 was interrupted. The outputs on Schmitt triggers 126 and 127 are also connected to a special transistor flip-flop 128 which will change state every time one of Schmitt triggers 126 and 127 produces an output. Again, no ambiguity will result since the Schmitt triggers never operate simultaneously. The output of flip-flop 128 and 146 is either zero or positive. The voltage on line 146 will thus change from one fixed state to the other (zero or positive voltage) each time either of the two light beams is interrupted as a result of the approach of an extreme position by slab 55 of phase-shifter 9.

Operational amplifier 116 has a variable gain unit 124, containing a field effect transistor, integrally connected to it. The gain of amplifier 116 and variable gain unit 124 combined depends on the magnitude of the signal on line 142. A near zero signal on line 142 causes the signal on line 139 to be amplified greatly by amplifier 116. A large signal on line 139 causes amplifier 116 to have a gain close to unity. In this manner, the control loop gain becomes a function of the load 4 reflection coefficient magnitude. The smaller the reflection coefficient, the larger the gain of amplifier 116 will be.

The output from amplifier 116 on line 143 is passed directly to amplifier 130, as well as through switch 125 and amplifier 118 to amplifier 130. Switch 125 contains another filed effect transistor. Zero voltage on line 146 means that switch 125 is on, while a positive voltage on line 146 turns switch 125 off. Operational amplifier 118 has a gain of minus two. Consequently, the sum of the signals on lines 143 and 144 is equivalent to either plus one times the output from amplifier 116 or to minus one times the output from amplifier 116. Thus, turning switch 125 alternately on and off by means of the signal on line 145 constitutes reversal of the sign of the control loop gain.

Integrated circuit operational amplifier 130 sums and amplifies the signals on lines 143, 144, 145 and merely adds the signal on line 141.

Final voltage amplification is supplied by power amplifier 119 which is capable of also delivering a high current signal to the drive coil of series line phase-shifter 9 via line 24.

All of the integrated circuit operational amplifiers, the two power amplifiers, the two Schmitt triggers, the flip-flop, as well as the light bulbs and photocells on phase-shifter 9 are supplied with plus and minus 15 volts DC power as required, by means of two power supplies 131 and 132. Power supplies 131 and 132 convert AC line power to extremely well filtered and highly regulated DC power of the proper voltage for operation of the entire electronic control unit 21.

There has been described above, an embodiment which is an impedance matching device for automatically and continuously matching a time varying microwave load to a fixed frequency microwave power source and its output line. More particularly, an improved method of sensing the degree of mismatch of a load to a microwave power source and its output line is described and a method of using the degree of mismatch information to adjust continuously two variable waveguide elements of novel design in such a manner that the load becomes matched to the microwave power source and its output line in a minimum amount of time, and remains matched despite wide variations with the passage of time in the value of the load.

The described apparatus, after initial adjustment to make it operational, requires no attention by a human operator to obtain and maintain a condition of match between a microwave power source and its load. The necessary adjustments of two variable waveguide elements are carried out automatically in a minimum amount of time. After a condition of match is obtained the loading conditions are monitored continuously and corrections are very rapidly applied to compensate for variations of the load with time, thus producing a minimum of error in matching at all times. The apparatus is capable of accommodating very large and rapid changes in loading that would normally be difficult to control by human intervention. The apparatus, therefore, presents a considerable improvement over the heretofore used methods of maintaining matched conditions to produce maximum efficiency and minimum degradation of the microwave power source.

There is described above, an improved and novel means of sensing the degree of mismatch or match between a microwave power source and its load on a continuous basis and of transforming the information regarding the degree of mismatch between a microwave power source and its load into a set of two electrical error signals which are capable of being used, after further treatment, to control the adjustment of two waveguide elements.

The set of error signals is modified, changed and amplified to indicate the degree of mismatch in a novel manner such that the wave guide elements can be automatically adjusted rapidly and optimally to produce a matched condition, and such that the matching adjustments consume a minimum amount of time.

Two novel and improved electromechanically driven and controlled waveguide elements are described which are capable of continuously and rapidly carrying out adjustments to two waveguide parameters by such means as to obtain and maintain matched loading conditions.

The described apparatus embodies a degree of mismatch sensing device, an electronic control, and two elec-

tromechanically adjusted waveguide phase-shifters. THe degree of mismatch sensing device including three microwave crystal diode detectors with adjustable attenuator sections. The detector probes are arranged in special positions along the longitudinal direction of a waveguide section. The special spacing and positioning of the detector probes is a feature of the described embodiment. The electrical outputs from the detector probes enter the electronic control and are therein amplified and arithmetically combined by means of operational amplifiers to produce two error signals which are, in face, the real and imaginary vector components of the amplified load reflection coefficient. The special and particular arithmetic operations performed upon the detector output signals to produce the vector components of the load reflection coefficient are another feature of the described embodiment. The two reflection coefficient vector component signals are mixed with rate signals and further amplified in the electronic control to deliver two powerful electrical signals capable of affecting the motion and positioning of a pair of electromechanically driven waveguide phase-shifter elements. One of the phase-shifters is shorted at one end while its other end is connected to the main waveguide by means of a parallel waveguide tea. The other phase-shifter is inserted in the main waveguide between the load and the said parallel tee. The phase-shifters contain electromechanical devices to measure the rate and direction of motion of their adjustable elements and convert this information into electrical rate signals. The electromechanical means of moving and positioning the phase-shifter elements and of detecting the rate and direction of motion are features of this invention. Simultaneous adjustment of the two phase-shifters makes it possible to match the load to the microwave power source and its output line. For certain loading conditions the proper adjustment of the series line phase-shifter may lie outside its adjustment range. The series line phase-shifter and the electronic control, therefore, contain electro-optical means of detecting the exceeding of the adjustment range and of inverting the sign of the phase-shifter driving signal to bring the adjustment back within range. The means of keeping the adjustments within the range of the said phase-shifter is is a feature of the described apparatus. The parallel phase-shifter contains a means of automatically adjusting the magnitude of the rate of motion signal, depending upon the positioning of its adjustable element. Likewise, the series line phase-shifter portion of the electronic control embodies a means of automatically adjusting the rate of amplification of its driving signal, in accordance with the actual magnitude of the load reflection coefficient. These rates of motion and driving signal amplification controls make it possible to carry out matching adjustments in minimum time. Said means of assuring minimum time matching adjustments are also a feature of the described embodiment. Finally, it is a feature of the illustrated apparatus that the system for matching the load to a microwave source is a closed loop negative feedback system in which the two phase-shifter adjustments are carried out continuously and simultaneously.

As will be appreciated, the described system measures the real and imaginary vector components of the reflection coefficient presented by the combination of matching device and load as determined by the special microwave detector device. Corrections are then made to the matching device adjustments until both components of the reflection coefficient are zero.

The system uses waveguide phase-shifters for adjustment of only two waveguide parameters. These phase-shifters are driven by special linear motion electromechanical devices. THe load is matched at a particular chosen frequency and maintains a match despite rapid and continual changes in the load. The described system involves no sequencing. The two separate adjustments are made continuously and simultaneously. The necessary adjustments are also made as rapidly as possible independent of the degree of mismatch. To get minimum time or time-optimal matching, nonlinearities are purposely introduced into the system damping and loop gain. A sudden disturbance in the load will be corrected for within 10 milliseconds of time.

The device described above, is of course, mainly intended for use in the microwave frequency range from 1 to 100 gHz. where waveguides are used to interconnect the microwave power source, the matching device, and the waveguide load such as a heating cavity or a meander line.

The illustrated device uses only two servo-adjustable waveguide elements to match a waveguide load to a microwave power source. The adjustable elements are waveguide phase-shifters activated by special linear motion servomotors with rate of motion sensors attached. One such phase-shifter is connected in series between the power source and the load in the main waveguide, thus causing the line-length to the load to be electrically adjustable. The other such phase-shifter is connected in series with a waveguide short and is then connected in parallel with the main waveguide by means of parallel waveguide tee, thus forming an electrically adjustable shorted parallel waveguide stub.

The one sensing device illustrated contains three specially positioned microwave crystal detectors which sample either the electric or the magnetic field intensity in the main waveguide and converts this information into three DC signals related to power in the main waveguide. The main control unit amplifies and combines the three crystal detector outputs to produce two error voltages which are directly proportional to the real and imaginary vector components of the reflection coefficient of the combined microwave load and waveguide matching unit.

The described system contains two control loops that cause two adjustments to be made simultaneously. These two adjustments make it possible to match all loads with nonzero finite real parts. An additional control loop to bring the load within a matchable range of values is not required.

The described device uses no sequenced operations to obtain a matched load condition which here means a condition such that the reflection coefficient of the combined load and matching elements is zero. The control loops are active at all times and the matching operation is completely continuous. None of the linear servo drives are activated by relay or logic circuits. Any minute deviation from match will immediately cause corrective motion of the phase-shifters. The rate of corrective motion is mathematically related to the degree of mismatch occuring at any instant in time.

Furthermore, the described embodiment reduces three sensor outputs to two error voltages which activate two control loops that adjust two waveguide elements simultaneously and continuously. The error voltages are directly related to the loading conditions existing at any instant of time.

Means is provided to adjust the loop gain and the loop damping automatically and continuously while matching proceeds in accordance with the remaining degree of mismatch such as to optimize the motion of the phase-shifters in order to reduce the time required to obtain and maintain a matched condition.

I claim:

1. A microwave impedance matching system for matching a microwave input waveguide to a microwave output waveguide including:

a. a waveguide parallel tee connected to the output waveguide, said parallel tee including a parallel short circuit,

b. a mismatch sensing device associated with the input waveguide to sample the standing wave pattern therein and to provide signals indicative of the degree of mismatch of said input waveguide to said output waveguide;

c. a first waveguide phase-shifting device connected in said parallel tee between said input waveguide and said short circuit;

d. a second waveguide phase-shifting device connected in said output waveguide;

e. said first and second waveguide phase-shifting devices being capable of adjustment in response to said signals to change the value of admittance at the plane of symmetry of said waveguide parallel tee in a direction to reduce the degree of mismatch of said input waveguide to said output waveguide.

2. A microwave impedance matching system according to claim 1 wherein said mismatch sensing device comprises a plurality of microwave probes connected in the input waveguide to sample the standing wave pattern in the waveguide whereby the real and imaginary vector components. of a respective reflection component can be considered.

3. A microwave impedance matching system according to claim 1 wherein said signals are supplied to an electronic control unit capable of controlling the adjustment of said first and second waveguide phase-shifting devices in response to said signals.

4. A microwave impedance matching system according to claim 3 wherein each waveguide phase-shifting device provides a respective rate signal to the electronic control unit indicative of its rate of adjustment and the direction of said adjustment, said electronic control unit responding thereto to control the respective adjustment and provide a braking action whereby the respective adjustment is stopped substantially at a position corresponding to said degree of mismatch being at a minimum.

5. A microwave impedance matching system according to claim 4 including a waveguide directional coupler device connected in the output waveguide and an associated crystal detector to provide a signal to the electronic control unit proportional to the square of the reflection coefficient of the output waveguide, whereby the adjustment of said second waveguide phase-shifting device is a function of the magnitude of said reflection coefficient.

6. A microwave impedance matching system according to claim 4 wherein said second waveguide phase-shifting device includes limit indicating means to indicate when the adjustment thereof is at an upper or a lower limit.

7. A microwave impedance matching system according to claim 6 wherein said limit indicating means comprises an electric lamp at said upper and said lower limit, the light beam from each lamp being incident, in use, on a respective photocell, each respective light beam being interrupted when said adjustment is at the respective limit whereby a respective upper or lower limit signal is provided to said electronic control unit.

8. A microwave impedance matching system according to claim 1 wherein each waveguide phase-shifting device comprises a dielectric slab member mounted on a nondielectric pin member having its longitudinal axis transverse to the respective waveguide whereby the respective slab can be moved transversely in the waveguide to permit adjustment of the differential phase-shift.

9. A microwave impedance matching system according to claim 8 wherein each pin member is slidable in sleeve bearings extending through the sidewalls of the waveguide, one end of each pin being attached to a drive coil which is movable in a magnetic field parallel to the longitudinal axis of the pin in response to current flowing through it, the other end of each pin having attached thereto a rate coil movable in a magnetic field to provide a rate signal proportional to the rate of movement of the respective slab member.

10. A microwave impedance matching system according to claim 9 wherein said rate coil of said first waveguide phase-shifting device is a multilayer cylindrical coil constructed with some layers shorter in length than other layers whereby a rate signal is obtained indicative of the velocity of the respective dielectric slab and its position in the respective waveguide.

11. A microwave impedance matching system according to claim 9 wherein said second waveguide phase-shifting device includes limit indicating means to indicate when the adjustment thereof is at an upper or a lower limit.

12. A microwave impedance matching system according to claim 11 wherein said limit indicating means comprises an electric lamp at said upper and said lower limit, the light beam from each lamp being incident, in use, on a respective photocell, each respective light beam being interrupted when said adjustment is at the respective limit whereby a respective upper or lower limit signal is provided to said electronic control unit.

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