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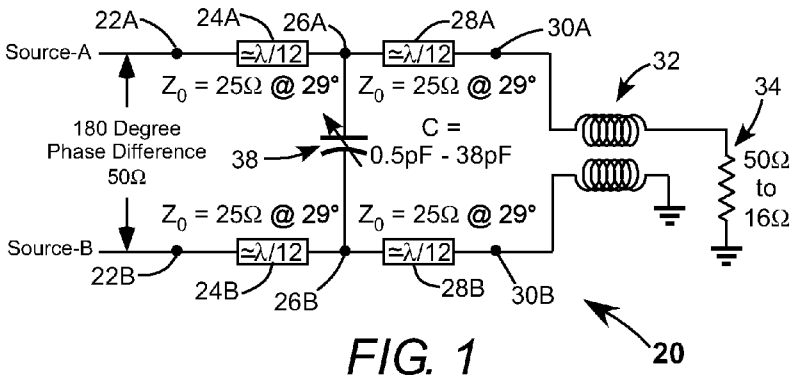


FIG. 1

(57) Abstract: Electrical apparatus for connecting a radio frequency power- supply having two outputs (Source A- Source B) to a load includes two radio frequency transmission - lines, each one connected to a corresponding power-supply output, transformer arrangement connects the two transmission - lines to the load (34). Each transmission - line includes a series - connected pair of twelfth- wave transmission - line sections (24A, 24B, 28A, 28B). The series - connection (26A) between the twelfth wave transmission - line sections in one transmission line i connected to the series - connection (26B) between the twelfth-wave transmission - line sections in the other by a device (38) having an adjustable impedance.

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IMPEDANCE-MATCHING CIRCUITS FOR MULTI-OUTPUT POWER SUPPLIES DRIVING CO_2 GAS-DISCHARGE LASERS

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TECHNICAL FIELD OF THE INVENTION

The present invention relates in general to impedance matching a radio frequency power supply (RFPS) to a load provided by discharge electrodes and related components in a radio frequency (RF) driven CO_2 gas-discharge laser. The invention relates in particular to impedance matching an RFPS having a plurality of outputs, or a plurality of RFPSs, to the load.

DISCUSSION OF BACKGROUND ART

It is well known the for optimum power transfer from a RFPS to a load an impedance-matching circuit is required. The output power of a CO_2 gas discharge laser increases directly with increasing discharge volume. The RF input (load) impedance of the laser varies inversely as the output power and decreases directly as the area of the discharge. The load impedance can vary between lasers within the same model family due to variations in discharge gas pressure, spacing between the electrodes, and other factors. Because of this, it is desirable to have an impedance-matching circuit that has a selectively variable impedance, such that a power supply having a fixed output impedance can be matched precisely to any one of a family of lasers having a load impedance anywhere within an anticipated range for that family.

U.S. Patent Application No. 12/786,199, by Hauer et al., assigned to the assignee of the present invention, and the complete disclosure of which is hereby incorporated by reference, describes an impedance-matching circuit comprising two series-connected lengths of transmission line, each thereof having an electrical length of about one-twelfth (1/12) wavelength at an operating frequency of the circuit, for matching the impedance of an RF power supply to a load. The impedance of the circuit is made selectively variable by connecting a variable impedance shunt to ground to a node between the two transmission line lengths. The variable impedance shunt can be a variable resistor, a variable capacitor, or a variable inductor. This arrangement has an advantage that a range of load impedances can be

accommodated with a common transmission-line length. This reduces parts inventory in a manufacturing process for a family of lasers.

A disadvantage of the above discussed Hauer et al. arrangement is that it provides only for matching the impedance of a single-ended power supply to a load. In driving high power lasers it may be desirable to use in the power supply the output of a plurality of RF amplifiers with each being a separate output (end) of the power supply. This is because the power output of one RF amplifier can be limited by the power handling capability of amplifier components such as power transistors. There is a need for an impedance-matching circuit that is capable of connecting a multi-ended power supply to a load while still preserving advantages of the Hauer et al. arrangement.

SUMMARY OF THE INVENTION

The present invention is directed to an impedance-matching network for connecting a plurality of radio-frequency power-sources to a load. The network has an input impedance and an output impedance and the load has a load impedance.

One aspect of the inventive network comprises a plurality of radio frequency transmission-lines equal in number to the plurality of radio frequency power sources having a source impedance. Each transmission-line is connected to a corresponding one of each of the power sources with the transmission lines being connected to the load via a first radio frequency combiner. Each transmission-line includes a pair of series connected transmission line sections with each section in the pair having an electrical length of about one-twelfth of a wavelength at an operating frequency of the power-sources. The series-connection between the transmission-line sections in one pair thereof being connected to the series-connection between the first and second transmission-line sections in a pair thereof in at least one other transmission-line by a device having an impedance adjustable within a first predetermined range for matching one of the input and output impedance of the network to respectively one of the source impedance and the load impedance.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 schematically illustrates one preferred embodiment of impedance matching network circuitry in accordance with the present invention used for matching the output impedance of two RF-power sources having a fixed load impedance and a 180-degree phase-difference therebetween to a load which can have a load impedance varying within a

predetermined range, the network including two identical pairs of series-connected twelfth-wave transmission-lines sections one connected to each of the source with the output of the pairs combined and connected to the load via a balanced-to-unbalanced (BalUn) transformer and variable impedance matching provided by a variable capacitance shunt between junction points of transmission line sections in the pairs thereof.

FIG. 2 schematically illustrates another preferred embodiment of impedance matching network circuitry in accordance with the present invention similar to the embodiment of FIG. 1 but wherein the load impedance is fixed and the output impedance of the sources can vary within a predetermined range.

FIG. 3 schematically illustrates yet another preferred embodiment of impedance matching network circuitry in accordance with the present invention similar to the embodiment of FIG. 2 but wherein the two separate sources are replaced by a final amplifier stage comprising two FETs in a push pull arrangement with each of the pairs of transmission line sections connected to a corresponding one of the FETs.

FIG. 4 schematically illustrates still another preferred embodiment of impedance matching network circuitry in accordance with the present invention similar to the embodiment of FIG. 3 but wherein the variable capacitance is provided by a bank of six capacitors automatically switchable alone or in any parallel combination thereof in response to monitored values of power-output and efficiency of the circuit.

FIG. 4A schematically illustrates the variable capacitor from Figure 4 in more detail.

FIG. 5 schematically illustrates still yet another embodiment of an impedance matching network in accordance with the present invention configured for impedance matching two separate RF sources having a variable output-impedance to a single load having a fixed input impedance with zero phase-difference between the outputs of the RF sources. This embodiment is similar to the embodiment of FIG. 2 with exceptions that the BalUn transformer is replaced by a coaxial zero-degree two-way combiner for combining outputs of the transmission line pairs and variable impedance between the line pairs is

provided by another zero-degree two-way combiner shunted to ground by the variable capacitance.

FIG. 6 schematically illustrates an additional embodiment of an impedance matching network in accordance with the present invention configured for impedance matching two separate RF sources having a variable output-impedance to a single load having a fixed input impedance, the embodiment being similar to the embodiment of FIG. 5 with an exception that the variable capacitance is provided by a transmission line stub having an incrementally variable length.

FIG. 7 schematically illustrates another additional embodiment of an impedance matching network in accordance with the present invention configured for impedance matching two separate RF sources having a variable output-impedance to a single load having a fixed input impedance, similar to the embodiment of FIG. 5 but wherein the variable capacitance is provided by a bank of capacitors automatically switchable alone or in any parallel combination thereof in response to monitored values of power-output and efficiency of the circuit.

FIG.8 schematically illustrates yet another additional embodiment of an impedance matching network in accordance with the present invention for impedance matching two separate RF sources having a variable output impedance and zero phase-difference between the outputs, to a single load having a fixed input impedance.

FIG. 9 schematically illustrates still yet another additional embodiment of an impedance matching network in accordance with the present invention for impedance matching three separate RF sources having a variable output impedance and zero phase-difference between the outputs, to a single load having a fixed input impedance.

FIG 10 schematically illustrates a further embodiment 80, of an impedance matching network in accordance with the present invention for impedance matching two power amplifiers having different output powers with the outputs in phase.

FIG. 11 schematically illustrates one preferred embodiment of an impedance matching network in accordance with the present invention for powering two power amplifiers from a single RF input, with each power amplifier driving a corresponding one of two CO_2 lasers and with the output powers tunable by adjusting the value of a capacitor in an LC circuit.

FIG. 11A schematically illustrates another preferred embodiment of an impedance matching network in accordance with the present invention for powering two power amplifiers from a single RF input, similar to the embodiment of FIG. 11 but with each power amplifier driving a corresponding one of two pairs of discharge electrodes in a single CO_2 laser.

FIG. 12 is a graph schematically illustrating the impedance at the input of the network FIG. 11 as a function the frequency of the RF input for a particular value of the tuning capacitor.

FIG. 13 is a graph schematically illustrating the outputs of amplifiers of FIG. 11 as a function of frequency of the RF input for the particular value of the capacitor.

FIG. 14 schematically illustrates a preferred embodiment of an impedance matching network in accordance with the present invention for powering a dipole antenna.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the drawings, wherein like features are designated by like reference numerals, FIG. 1 schematically illustrates one preferred embodiment of impedance matching network circuitry in accordance with the present invention, arranged to match the output of two RF sources (Source-A and Source-B) having a fixed output-impedance across nodes 22A and 22B, but with a 180-degree phase-difference therebetween to a single load 34 having a load-impedance Z_L which may vary, according to type, in an anticipated range. Here, fixed impedance across nodes 22A and 22B is 50 Ohms (Ω) and the anticipated load impedance range Z_L range is between 50 Ω and 16 Ω.

Node 22A from Source-A is connected to length of transmission line section 24A having a characteristic impedance Z_0 of 25Ω and an electrical length of slightly less than one-

twelfth wave at the design RF frequency, here assumed to be 100 MHz. In the drawing of FIG. 1, and other drawings describing other embodiments of the present invention, electrical lengths of transmission lines are designated in degrees (360° being equal to one-wavelength) or fractional wavelengths (with λ being equal to one wavelength), whichever is deemed more convenient. In this example, transmission line section 24A has a length of 29° (λ/12 = 30°).

Transmission line section 24A is connected to another transmission line section 28A of the same characteristic impedance and electrical length via a node 26A therebetween. Node 22B from Source-B is connected to transmission line sections 24B and 28B in series via node 26B therebetween. Transmission line sections 24B and 28B have the same characteristics as sections 24A and 28A. This arrangement is known to practitioners of the art as a 180-degree symmetrical network. Nodes 30A and 30 B at the output of transmission line sections 28A and 28B, respectively, are connected via a balanced-to-unbalanced (BalUn) transformer 32 to load 34.

Each connection line to the transformer, or an equivalent combiner, from the corresponding source can be defined as a "load-line", that is to say, a load-transmission line. In any such load-line, there will be, at a minimum, the first and second twelfth-wave transmission line sections, universally designated herein by reference numerals 24 and 28, with appropriate subscripts A, B or C, depending on the number of sources and corresponding load-lines.

Matching to the variable load impedance of load 34 is accomplished in circuit 20 by connecting a selectively variable, *i.e.*, adjustable, impedance between nodes 26A and 26B. In this example, the adjustable impedance is a selectively variable capacitance 38 having a capacitance C which can be varied between 0.5 picofarads (pF) and 38.0 pF, for an impedance match between 50Ω and 16Ω, respectively, of load 34. The values for capacitor 34, and for other circuit components in other embodiments of the inventive circuitry described hereinbelow, were calculated using circuit-simulation software PSpice™ available from Cadence Design Systems Inc., of San Jose, California.

The circuitry of FIG. 1 can be used to match sources having an output impedance which varies, according to type, to a particular load which has a fixed impedance. This is illustrated in FIG. 2 as an another preferred embodiment 20A of the present invention, wherein the variable-capacitance-shunted transmission symmetrical network of arrangement 20 is used to match a load 34A having a load impedance of 50Ω to a pair of sources which may provide an impedance across nodes 22A and 22B of between 50Ω and

16Ω. This variation is accommodated, as discussed above, by adjusting the capacitance of variable-capacitance 38 between 0.5 pF and 38.0 pF.

FIG. 3 schematically illustrates yet another preferred embodiment of impedance matching network circuitry in accordance with the present invention similar to the embodiment of FIG. 2 but wherein the two separate RF sources are replaced by a final amplifier stage comprising two field effect transistor (FETs) 40A and 40B in a push-pull arrangement. Here the drain (D) of FET 40A is connected to node 22A and the drain of FET 40B is connected to node 22B. DC power for powering the amplifier stage is coupled to the two FETs from a source P, via RF chokes L_1 and L_2. The signal being amplified is applied to gates G of the FETs and the sources of the FETs are commonly grounded. Impedance matching is accomplished as described above via selectively variable capacitance 38 for adjusting the output power and efficiency of the final amplifier stage.

FIG. 4 and FIG. 4A schematically illustrate still another embodiment 20C of the present invention similar to the embodiment of FIG. 3 but wherein the impedance matching and corresponding efficiency optimization are automated. In order to facilitate this automation, variable capacitance 38 is implemented in embodiment 20C as a plurality of individual capacitances C_1, C_2, C_3, C_4, C_5 and C_6 that can be connected between nodes 26A and 26B, alone or in various parallel combinations. Connection is effected by RF relays 44 (collectively depicted) operating corresponding switches as illustrated (see FIG. 4A for detail). Such relays are commercially available incorporated in a multi-pole relay model S172 from Teledyne Relays Inc., of Hawthorne, California.

In circuit 20C, capacitors C_1-C_6 have values 2 pF, 4 pF, 8 pF, 16 pF, 32 pF and 64 pF respectively. This enables total capacitance to be varied from 2 pF to 126 pF in increments of 2 pF for matching a balanced FET load varying from 45Ω to 12Ω, respectively. Relay-coil connections, DC blocking capacitor connections and other well-known details of the switching arrangement are not shown for simplicity of illustration. Relays 44 may be by replaced by other suitable switching technology such PIN-diode switching devices.

DC voltage is supplied to the FETs from a DC voltage (DCV) source 46 through RF chokes L_1 and L_2 as described above with reference to FIG. 3. A power control logic module 48 monitors the DC voltage and current via a voltage and current sensor 50, and monitors output power of the network via a power monitor 52. A user inputs required power and efficiency value settings to the control module as illustrated in FIG. 4. The control module calculates required capacitance for achieving the set values and instructs relays 44 to

switch accordingly to provide the necessary combination of capacitors C_1-C_6. Power output of the network is delivered to a CO_2 laser 54 having a load impedance of 50Ω.

FIG. 5 schematically illustrates still yet another embodiment 60 of an impedance matching network in accordance with the present invention. Network 60 is configured for impedance matching two separate RF sources having a variable output impedance, to a single load having a fixed input impedance. In this embodiment the sources are represented by final FET amplifier stages 62A and 62B. Here there is zero phase-difference between the outputs of the FETs with an output impedance of each one which can vary between 25Ω and 12Ω.

The network includes twelfth-wave transmission line section pairs 24A and 28A, and 24B and 24B as in above-described embodiments. In FIG. 5, these, and other transmission line sections are represented as lengths of 25Ω coaxial cable. As they are functionally equivalent to above-described transmission line sections, and have the same electrical characteristics, the original reference numerals are retained to assist comparison of embodiments.

Because there is zero phase difference between inputs to the transmission line sections, it is not possible to connect a variable tuning capacitance directly between nodes 26A and 26B between the transmission line sections. In this embodiment, a length of transmission line 64 is connected as a zero-degree two-way combiner which combines the in-phase currents at nodes 26A and 26B. Transmission line 64 has a characteristic impedance of 25Ω and an electrical length of about λ/20, *i.e.*, 18°. Transmission line section 64 delivers an RF signal to one end of a selectively variable capacitor 39, the other end of which is connected to ground.

The capacitance of capacitor 39 can be varied to adjust the individual output impedances of the FETs in the range between 25Ω and 12Ω. Doing so adjusts saturated peak-to-peak voltage in the inventive variable impedance network thereby adjusting the output power and efficiency of the amplifier stage. Varying the capacitance between 5 pF to about 90 pF adjusts output impedances in the 25Ω to 12Ω range. A transmission line section 66 having the same characteristics as transmission line section 64 replaces the Balun transformer of above-described embodiments. This transmission line section is also connected as a zero-degree two-way combiner and combines the currents from nodes 30A and 30B to be in phase at node 31 which is connected to a fixed load 34B having an impedance of 12.5Ω.

FIG. 6 schematically illustrates still an additional embodiment 60A of an impedance matching network in accordance with the present invention. Embodiment 60A is similar to above-described embodiment 60 with an exception that variable capacitance 39 of embodiment 60 is replaced in embodiment 60A by a transmission-line stub 68 including a minimum-length section 67 and a variable section 69 which can be incrementally varied in length by adding by adding or subtracting one or more of a plurality of incremental sections 69 (only one designated in FIG 6) using a wire bridging connection (not shown). Independent of how many sections are connected (or not connected), the characteristic impedance, here 15Ω, and total electrical length, here 24°, will stay the same. The capacitance, however, will vary accordingly, to the amount of incremental sections connected, in this example, in incremental values between 5pF and 90 pF.

FIG. 7 schematically illustrates another additional embodiment 60B of an impedance matching network in accordance with the present invention. This is essentially embodiment 60 controlled by a logic controller and sensors as described above with referenced to FIG. 4. In embodiment 60B variable capacitance 39 is replaced by a relay-switched capacitor bank 38 similar to that described above with reference to FIGS 4 and 4A.

FIG.8 schematically illustrates yet another additional embodiment 70 of an impedance matching network in accordance with the present invention for impedance matching two separate RF sources having a variable output impedance and zero phase-difference between the outputs, to a single load having a fixed input impedance. The RF sources are represented by final-amplifier-stage FETs 62A and 62B. This embodiment is similar to embodiment 60 of FIG. 5 with an exception that zero-degree two-way combiner 66 of embodiment 60 is replaced in embodiment 70 by a parallel $\lambda/2$ transmission line sections 72A and 72B the outputs of which are combined at a common node 74 connected to fixed load 34B.

FIG. 9 schematically illustrates still yet another additional embodiment 70A, of an impedance matching network in accordance with the present invention, here, for impedance matching three separate RF sources, 62A, 62B, and 62C having a variable output impedance and zero phase-difference between the outputs, to a single load having a fixed input impedance. This embodiment is similar to above described embodiment 70 of FIG. 8 with an exception that, in order to accommodate the third source 62C, another load line including two approximately twelfth-wave sections 24C and 24C is added with corresponding nodes 22C, 26C, and 30C.

Instead of the single λ/20 length of transmission line 64 used as a current combiner in embodiment 70 a zero-degree three-way combiner 76 is formed from three similar lengths of transmission line 64A, 64B, and 64C connected as an equal-delay combiner. Currents from nodes 26A-C are combined by combiner 76 at a common node 78 and shunted to ground through selectively variable capacitance 39 to ground as discussed above to effect adjustable impedance-matching. In theory at least, four or more sources may be combined as depicted in FIG. 9.

TABLE 1

Capacitor 39 (pF)	Total Input Power At all nodes 22	Input Impedance at each node 22	Output Power Total at node 74A
1 pF	5784 Watts	24.8 Ohms	5688 Watts
20 pF	5802 Watts	22.7 Ohms	5697 Watts
30 pF	5796 Watts	21.5 Ohms	5685 Watts
50 pF	5751 Watts	19.2 Ohms	5619 Watts
60 pF	5703 Watts	18.1 Ohms	5565 Watts
70 pF	5640 Watts	16.9 Ohms	5493 Watts
80 pF	5556 Watts	15.9 Ohms	5406 Watts
90 pF	5454 Watts	14.8 Ohms	5301 Watts
100 pF	5328 Watts	13.8 Ohms	5181 Watts
120 pF	5028 Watts	11.8 Ohms	4890 Watts

Table 1 depicts calculated values of total input power and total output power in the circuit of FIG. 9 for various values of capacitor 39. The decrease in input and output power is due to increasing circuit losses as the input impedance of the circuit was decreased by increasing the value of capacitor 39.

In all of the above described embodiments the radio frequency sources in any one all have about the same output power. FIG 10 schematically illustrates a further embodiment 80, of an impedance matching network in accordance with the present invention, here for impedance matching two power amplifiers 82A and 82B having different output powers with the outputs in phase. In the example of FIG. 10 it is assumed that the output power ratio is 2:1. Each amplifier has a nominal output impedance of 25Ω. Embodiment 80 is similar to embodiment of FIG. 5 inasmuch as it includes the network of two pairs of twelfth-wave transmission line sections 24A and 28A, and 24B and 28B with currents at

nodes 26A and 26B thereof combined by zero-degree two-way combiner 64 shunted to ground at one end thereof by a selectively variable impedance (reactance) 85.

In embodiment 80 however a λ/4 (90°) length of 25Ω transmission line 84 is inserted between amplifier 82A and transmission line section 24A to drive the (A) side of the network in quadrature with the opposite (B) side. A complementary length of 25Ω transmission line 86 is inserted between transmission line section 28B and zero-degree two-way combiner 66 for offsetting the phase-shift introduced by transmission line section 84.

In variable reactance 85, a fixed inductance L_3 is connected in parallel with variable capacitance 37 in the shunt to ground. By operating in quadrature, the tuning reactance, 85, is allowed to continuously change from inductive to capacitance. This is to offset the tuning of capacitor 37 and allow the input impedances of the A and B sides of the network to be tuned through a midpoint where the impedances are equal. This means that it does not matter which amplifier has the higher output power. For an adjustment range of capacitor 37 between 5 pF and 150 pF, the inductance value of L_3 is preferably 48 nanohenries (nH).

The circuit arrangement of embodiment 80 allows the combining of the outputs of amplifiers of different output powers without loss of combining efficiency. By way of example, an amplifier of 1000W output may be combined in phase with another amplifier of 600W output to achieve (minus circuit losses) 1600 W of total output. Calculations performed for the values shown in FIG. 10 indicate that one input can be 1000 W and the other input can varied from 390 W, when C = 17pF, to 1590 W when C = 72pF. Total combined power at node 31 is 1315 W to 2472 W for the range of values indicated for capacitor 37. Calculations indicate that small changes in input impedance of the A and B sides of the network due to the tuning of the capacitor 30 remain within a voltage standing wave ratio (VSWR) of 1.15:1 relative to the nominal 25Ω design center. Small variations in the actual input power at node 22A are due to such changes in the input impedance.

TABLE 2

Capacitance 37	Zin at Node 81	Zin at Node 22B	Power at Node 81	Power at Node 22B	Output at Node 31
17pF	26.9 Ohms	27.1 Ohms	922 W	390 W	1315 W
27pF	26.5 Ohms	26.5 Ohms	934 W	567 W	1511 W
47pF	25.6 Ohms	25.6 Ohms	969 W	969 W	1894 W
60pf	24.8 Ohms	24.9 Ohms	983 W	1279 W	2184 W
72pF	24.1 Ohms	25.0 Ohms	982 W	1590 W	2472 W

TABLE 2 provides a summary of the above discussed analysis of the variation in impedance at nodes 81 and 22B of FIG. 10 for various values of capacitor 37. It can be seen that that the impedances at nodes 81 and 22B are approximately the same while the total power at node 31 is about equal to the sum of the power at nodes 81 and 22B for all practical purposes. Impedances are close to the design nominal 25Ω as discussed above.

In all of the above-discussed embodiments of the present invention an object is to drive a single laser using the combined power outputs of two or more sources. It is sometimes required, however to combine output of two lasers when one is insufficient to provide required laser power. Alternatively it may be required to drive a single laser having cascaded sets of electrodes.

Cascaded electrodes may be used, for example to increase the impedance of the load to make impedance matching easier. This reduces the amount of power that an RF power supply needs to provide, thereby reducing the circulating currents within the impedance matching network. Reducing the circulating currents reduces the size of the components within the impedance matching network and makes the discharge easier to light. Another reason for using cascaded electrodes is that in order to increase laser power it is necessary to increase the length of the electrodes thereby making the gas-discharge region longer. Eventually electrode lengths are reached which make it very difficult to keep the electrodes sufficiently parallel to one another to prevent distorting the wave-guiding of the laser beam provided by the electrode surfaces.

The distortion occurs because the electrode surfaces facing the discharge become hotter than the opposite surfaces not facing the discharge. This causes a thermal gradient across the thickness of the electrodes which in turn causes bending moments. Such bending causes the spacing between the electrodes to be larger in the center than at the ends, particularly if the ends of the electrodes are held in a fixed position.

FIG. 11 schematically illustrates one preferred embodiment 90 of an impedance matching network in accordance with the present invention configured for powering two power amplifiers 92A and 92B from a single RF input. Amplifiers 92A and 92B drive corresponding CO_2 lasers 94A and 94B. In this example laser 94A is driven at a power of 2.37 kilowatts (kW) and laser 94B is driven at a power of 1.38 kW. The input impedance (Z_{IN}) at node 31 is 12.5Ω. Amplifiers 92A and 92B each have Z_{IN} equal to 25Ω.

The impedance matching network of FIG. 11 is essentially the network of FIG. 10 used in reverse. Accordingly, reference numerals for components of embodiment 80 have been retained for corresponding components of embodiment 90. In embodiment 90, zero-degree two-way combiner 66 of FIG. 10 is used as a two-way splitter and divides an RF input signal along the A and B arms of the network. The amount of power in each of the network arms is varied by adjusting capacitor 37 of LC circuit 85 as in embodiment 80. Quarter-wave transmission line section 86 is inserted ahead of node 22A to drive the A side of the twelfth-wave section network in quadrature with the B-side thereof. Quarter-wave transmission line section 86 is inserted after node 30B to compensate for the 90° phase-shift caused by section 66. Calculations indicate that the input impedance at the amplifiers remains within 1.25:1 VSWR relative to the nominal 25Ω design center for a symmetrical output power variation of ± 500W from a nominal 1870W null condition.

FIG. 11A schematically illustrates another embodiment 90A of an impedance matching network in accordance with the present invention for driving two RF amplifiers from one input. Embodiment 90A is similar to embodiment 90 of FIG. 11 with an exception that amplifiers 92A and 92B drive respectively electrode pairs 98A and 98B of a single CO_2 laser 96.

FIG. 12 is a graph schematically illustrating the impedance at node 31 as a function the frequency of the RF input for a value of capacitor 37 of 53.0 pF. It can be seen that at a design frequency of 100 MHz the impedance is close to the nominal 12.5Ω design value.

FIG. 13 is a graph schematically illustrating the outputs of amplifiers 92A (solid curve) and 92B (dashed curve) as a function of frequency of the RF input for a value of capacitor 37 of 53.0 pF. It can be seen that at the design frequency of 100 MHz the output powers are about equal at about 1900 W close to the nominal 1870 W value.

TABLE 3

Capacitance 37	Z_{IN} at Node 31	Output of Amp 92A	Output of Amp 92B
1pF	14.3 Ohms	1284W	2460W
53pF	12.9 Ohms	1900W	1900W
100pF	12.5 Ohms	2570W	1260W

TABLE 3 lists variations in calculated impedances at node 31 of FIG. 11 for selected values of the capacitance of capacitor 37 together with corresponding calculated power output of amplifiers 92A and 92B. These calculations were made at a nominal design frequency of 100 MHz.

FIG. 14 schematically illustrates a preferred embodiment 100 of an adjustable impedance matching network in accordance with the present invention arranged for driving a dipole antenna. In principle, this embodiment is similar in operation to above-described embodiment 90 inasmuch as an RF signal is split into two parts and delivered via a basic network of two pairs of twelfth-wave transmission line sections to two dipole elements 102A and 102B. The two pairs of transmission line sections comprise sections 24A and 28A in one load line (the A side of the network) and sections 24B and 28B in the other load line (the B side of the network). Node 26 A between sections 24A and 24B is connected to node 26B a selectively variable capacitance 3, here tunable from 5 pF to 35 pF.

The input RF signal is split into two parts by an unbalanced-to-balanced transformer 104 formed by a length of transmission line having a fixed (source) impedance of 50Ω, in this example. The outputs of transformer 104 are delivered via nodes 30A and 30B of the network to respectively the A and B sides of the network. There is a 180° phase-difference between the signals at nodes 30A and 30B. Node 22A of the A side of the network is connected to element 102A of the dipole antenna, and node 22B of the network is connected to element 102B of the dipole antenna. Tuning (adjusting) capacitor 35 between the values of 5 pF and 35 pF adjusts the balanced impedance at the dipole elements between 50Ω and 35Ω, respectively for optimizing power coupled into the dipole antenna.

In conclusion, the present invention is described above in terms of several preferred embodiments. The invention, however, is not limited to the embodiments described and depicted herein. Rather, the invention is limited only by the claims appended hereto.

WHAT IS CLAIMED IS:

1. An impedance-matching network for connecting a plurality of radio-frequency power-sources to a load, the network having an input impedance and an output impedance and the load having a load impedance, the network comprising:

a plurality of radio frequency transmission-lines equal in number to the plurality of radio frequency power sources having a source impedance with each transmission-line connected to a corresponding one of each of the power sources with the transmission lines being connected to the load via a first radio frequency combiner;

each transmission-line including a pair of series connected transmission line sections with each section in the pair having an electrical length of about one-twelfth of a wavelength at an operating frequency of the power-sources; and

the series-connection between the transmission-line sections in one transmission line being connected to the series-connection between the transmission-line sections in at least one other transmission-line, said connection including a device having an impedance adjustable within a first predetermined range for matching one of the input and output impedance of the network to respectively one of the source impedance and the load impedance.

2. The impedance matching network of claim 1, wherein the source impedance has a fixed value, the load impedance has a value within a second predetermined range and the adjustable impedance is adjusted such that the output impedance of the network matches the value of the load impedance.

3. The impedance matching network of claim 1, wherein there are two radio frequency sources with phase-difference of 180 degrees between outputs thereof and the adjustable impedance is an adjustable capacitance.

4. The impedance matching network of claim 3, wherein the first radio frequency combiner is a balanced-to-unbalanced transformer.

5. The impedance matching network of claim 1, wherein the load impedance has a fixed value, the source impedance has a value within a second predetermined range and the adjustable impedance is adjusted such that the input impedance of the network matches the value of the source impedance.

6. The impedance matching network of claim 5, wherein there is zero phase-difference between outputs of the plurality of radio frequency sources, and the adjustable impedance device includes a second radio frequency combiner arranged to connect together at a common node the series connections between twelfth-wave transmission line pairs in the plurality thereof with the common node shunted to ground via an adjustable reactance.

7. The impedance matching network of claim 6, wherein there are two radio frequency power sources having about the same output power and two transmission lines, the second radio frequency combiner is a zero-degree two-way combiner formed by a first single section of transmission line having an electrical length of about one-twentieth of a wavelength at the operating frequency of the radio frequency sources and the variable reactance is a variable capacitance.

8. The impedance matching circuit of claim 7, wherein the first radio frequency combiner is a zero-degree two-way combiner formed by a second single section of transmission line having an electrical length of about one-twentieth of a wavelength at the operating frequency of the radio frequency sources

9. The impedance matching network of claim 7, wherein the first radio frequency combiner includes first and second transmission line sections each having an electrical length of about one-half wavelength at the operating frequency of the radio frequency sources, the first half-wave transmission line section being connected in series with the twelfth wave transmission line section pair in one of the transmission lines and the second half-wave transmission line section being connected in series with the twelfth wave transmission line section pair in other of the transmission lines, with the first and second half-wave transmission line sections being connected at a common node and the common node being connected to the load.

10. The impedance matching network of claim 6, wherein there are three radio frequency power sources having about the same output power and three transmission lines, the second radio frequency combiner is a zero-degree three-way combiner formed by a first, second and third sections of transmission line each having an electrical length of about one-twentieth of a wavelength at the operating frequency of the radio frequency sources and the variable reactance is a variable capacitance.

11. The impedance matching network of claim 10, wherein the first radio frequency combiner includes first, second, and third transmission line sections each having an electrical length of about one-half wavelength at the operating frequency of the radio frequency sources, the first half-wave transmission line section being connected in series with a the twelfth wave transmission line section pair in a first of the three transmission lines, the second half-wave transmission line section being connected in series with the twelfth wave transmission line section pair in a second of the three transmission lines, with the first, second, and third half-wave transmission line sections being connected at a common node and the common node being connected to the load.

12. The impedance matching network of claim 6, wherein there are two radio frequency power sources having different output power and two transmission lines, one of the two transmission lines having a first transmission line section having an electrical length of one-quarter wavelength at the operating frequency of the radio frequency sources connected between the twelfth-wave transmission line section pair and a first of the two radio frequency sources and the other of the two transmission lines having a second transmission line section having an electrical length of one-quarter wavelength at the operating frequency of the radio frequency sources connected between the twelfth-wave transmission line section pair and the first radio frequency combiner, and wherein the second radio frequency combiner is a zero-degree two-way combiner formed by a first single section of transmission line having an electrical length of about one-twentieth of a wavelength at the operating frequency of the radio frequency sources and the variable reactance includes an inductor in parallel with a variable capacitance.

13. The impedance matching network of claim 12, wherein the first radio frequency combiner is a zero-degree two-way combiner formed by a second single section of

transmission line having an electrical length of about one-twentieth of a wavelength at the operating frequency of the radio frequency source.

14. An impedance-matching network for connecting a radio-frequency input signal to first and second radio frequency amplifiers and adjusting an output power ratio of the amplifiers, the network comprising:

a radio frequency power splitter arranged to divide the input radio frequency signal into first and second signal portions;

first and second transmission lines arranged to transmit respectively the first and second signal portions to respectively the first and second radio frequency amplifiers;

each transmission-line including a pair of series connected transmission line sections with each section in the pair having an electrical length of about one-twelfth of a wavelength at a frequency of the radio frequency signal input;

first and second transmission line sections each thereof having an electrical length of about one quarter-wavelength at the frequency of the radio frequency signal input, the first quarter-wavelength transmission line section being connected in the first transmission line between the power splitter and the twelfth-wave transmission line section pair and the second quarter-wavelength transmission line section being connected in the second transmission line between the twelfth-wave transmission line section pair and the second radio frequency amplifier;

the series-connection between the twelfth-wave transmission-line sections in the first transmission line being connected to the series-connection between the twelfth-wave transmission-line sections in the second transmission line by a radio frequency power combiner with the output of the combiner being shunted to ground by a circuit having an adjustable reactance; and

wherein adjusting the variable reactance adjusts the output power ratio between the amplifiers.

15. The impedance matching network of claim 14, wherein the radio frequency power splitter is a zero-degree two-way power splitter formed by a single section of transmission line having an electrical length of about one-twentieth of a wavelength at the frequency of the RF signal input.

16. The impedance matching network of claim 14, wherein the radio frequency power combiner is a zero-degree two-way power combiner formed by a single section of transmission line having an electrical length of about one-twentieth of a wavelength at the frequency of the RF signal input.

17. The impedance matching network of claim 14, wherein the first and second radio frequency amplifiers drive respectively first and second CO_2 lasers.

18. The impedance matching network of claim 14, wherein the first and second radio frequency amplifiers drive respectively first and second pairs of discharge electrodes in a CO_2 laser.

19. An impedance matching network for driving a dipole antenna having first and second elements from a radio frequency signal input, the network comprising:

a unbalanced-to-balanced transformer arranged to divide the radio frequency signal in a radio frequency power splitter arranged to divide the input radio frequency signal into first and second signal portions having a 180 degree phase-difference therebetween;

first and second transmission lines arranged to transmit respectively the first and second signal portions to respectively the first and second dipole elements;

each transmission-line including a pair of series connected transmission line sections with each section in the pair having an electrical length of about one-twelfth of a wavelength at a frequency of the radio frequency signal input with series connections between the twelfth-wave pairs being connected by device having an adjustable impedance; and

wherein adjusting the impedance of the variable impedance device adjusts the output impedance of the network at the dipole elements for optimizing power coupled into the dipole antenna.

20. The impedance matching network of claim 19, wherein the adjustable impedance device is an adjustable capacitor.

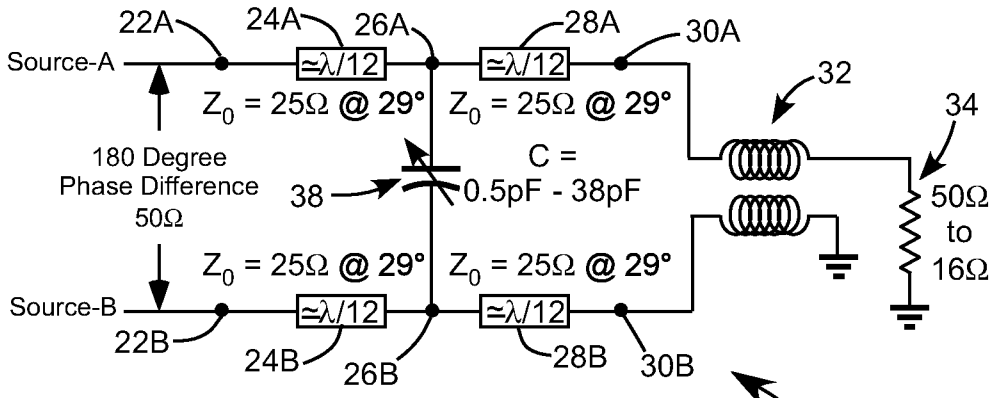


FIG. 1

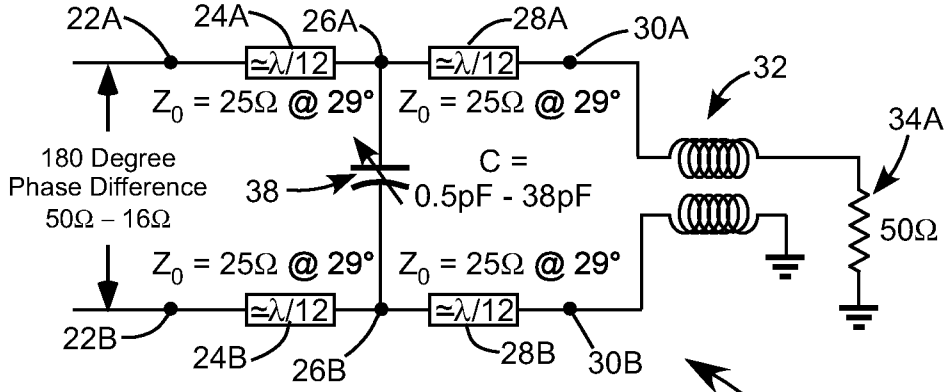


FIG. 2

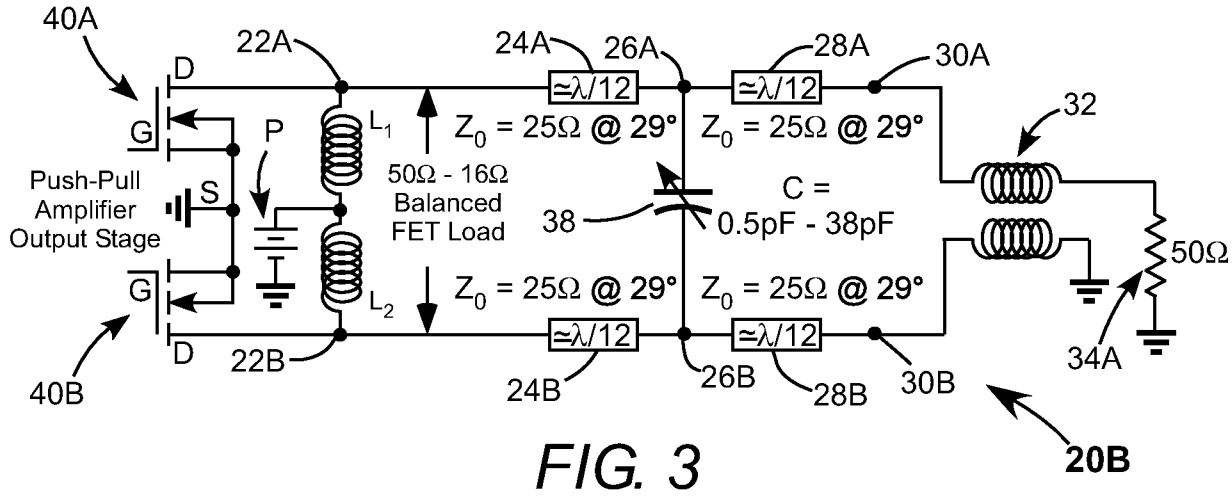


FIG. 3

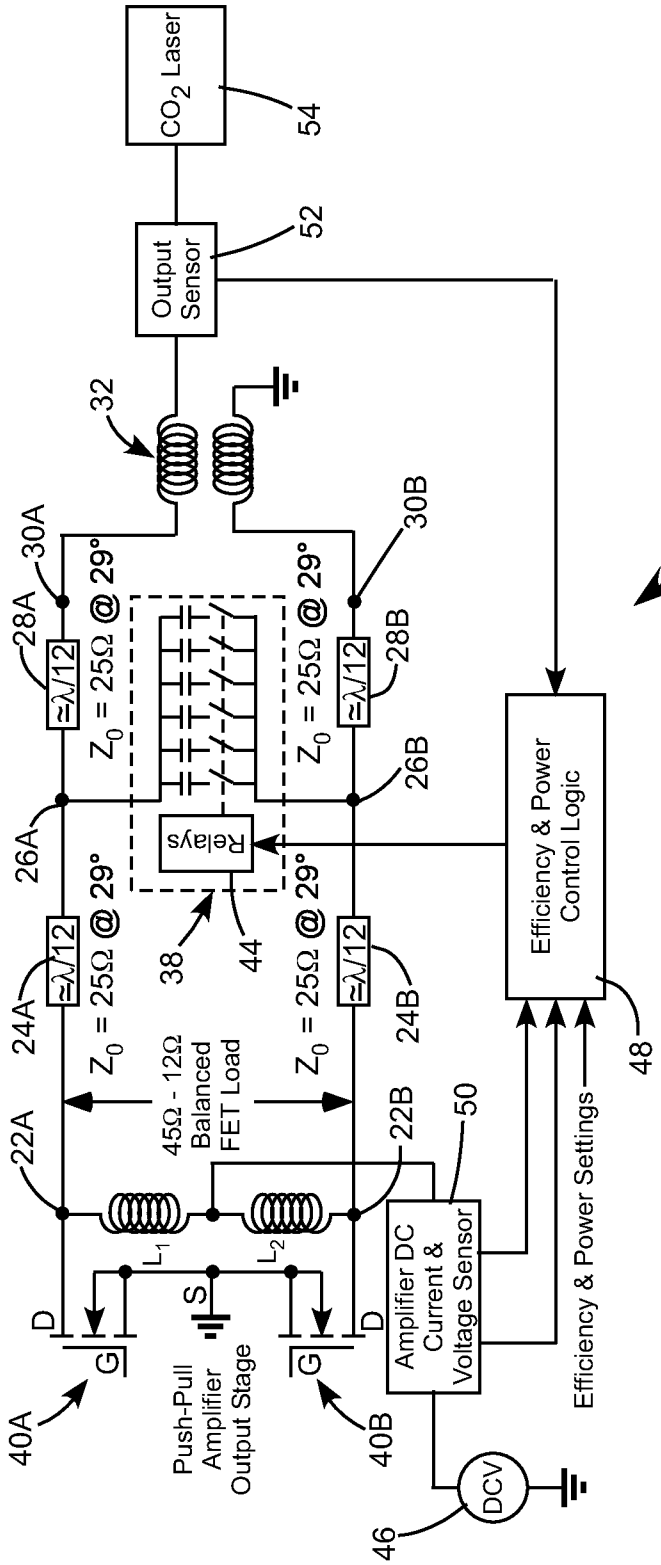

CO_2 Laser
54
Output Sensor
52
32
30A
30B
28A
28B
≈λ/12
Z_0 = 25Ω @ 29°
26A
26B
Relays
38
44
24A
24B
45Ω - 12Ω Balanced FET Load
22A
22B
50
L_1
L_2
S
D
G
40A
40B
Push-Pull Amplifier Output Stage
Amplifier DC Current & Voltage Sensor
DCV
46
Efficiency & Power Control Logic
48
Efficiency & Power Settings
20C

FIG. 4

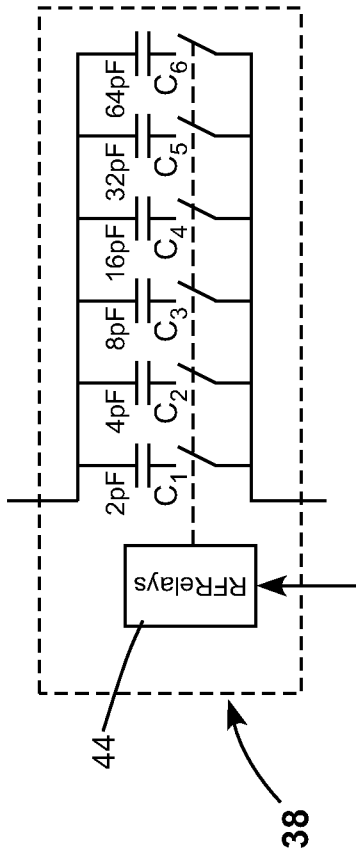

2pF
4pF
8pF
16pF
32pF
64pF
C_1
C_2
C_3
C_4
C_5
C_6
RFRelays
44
38

FIG. 4A

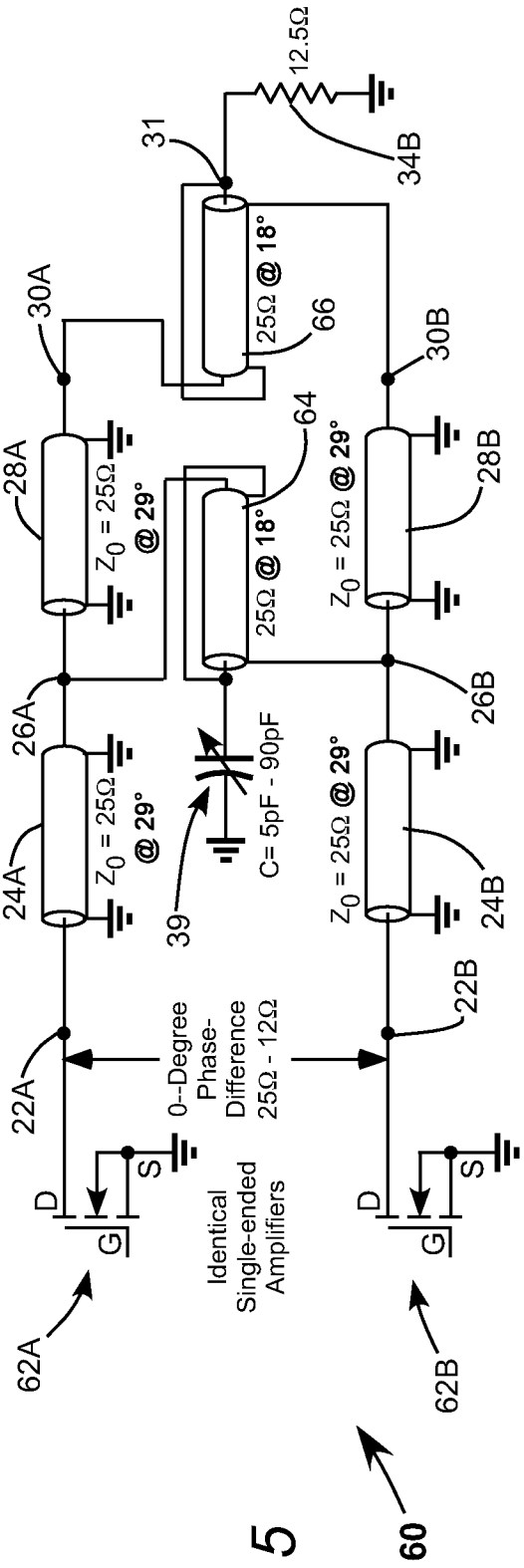

12.5Ω
31
34B
30A
30B
25Ω @ 18°
66
64
28A
28B
Z_0 = 25Ω @ 29°
25Ω @ 18°
Z_0 = 25Ω @ 29°
26A
26B
24A
24B
Z_0 = 25Ω @ 29°
Z_0 = 25Ω @ 29°
39
C= 5pF - 90pF
22A
22B
0--Degree Phase-Difference 25Ω - 12Ω
D
G
S
Identical Single-ended Amplifiers
62A
62B
60

FIG. 5

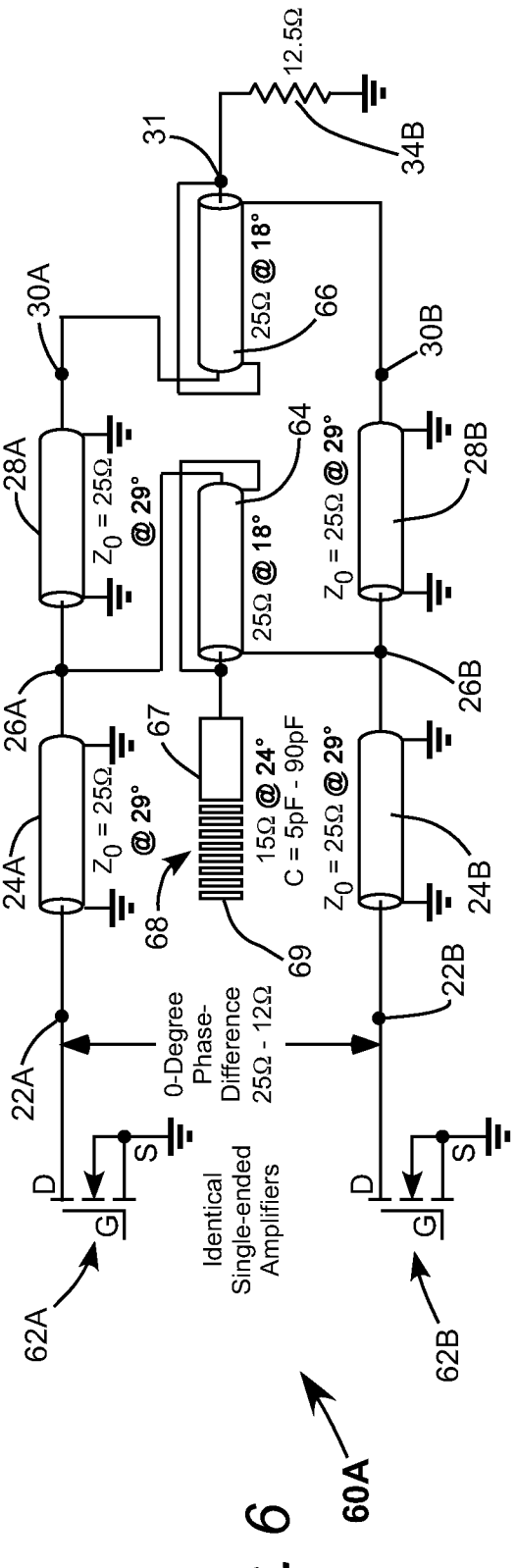

12.5Ω
31
34B
30A
30B
25Ω @ 18°
66
64
28A
28B
Z_0 = 25Ω @ 29°
25Ω @ 18°
Z_0 = 25Ω @ 29°
26A
26B
67
24A
24B
Z_0 = 25Ω @ 29°
15Ω @ 24°
C = 5pF - 90pF
Z_0 = 25Ω @ 29°
68
69
22A
22B
0-Degree Phase-Difference 25Ω - 12Ω
D
G
S
Identical Single-ended Amplifiers
62A
62B
60A

FIG. 6

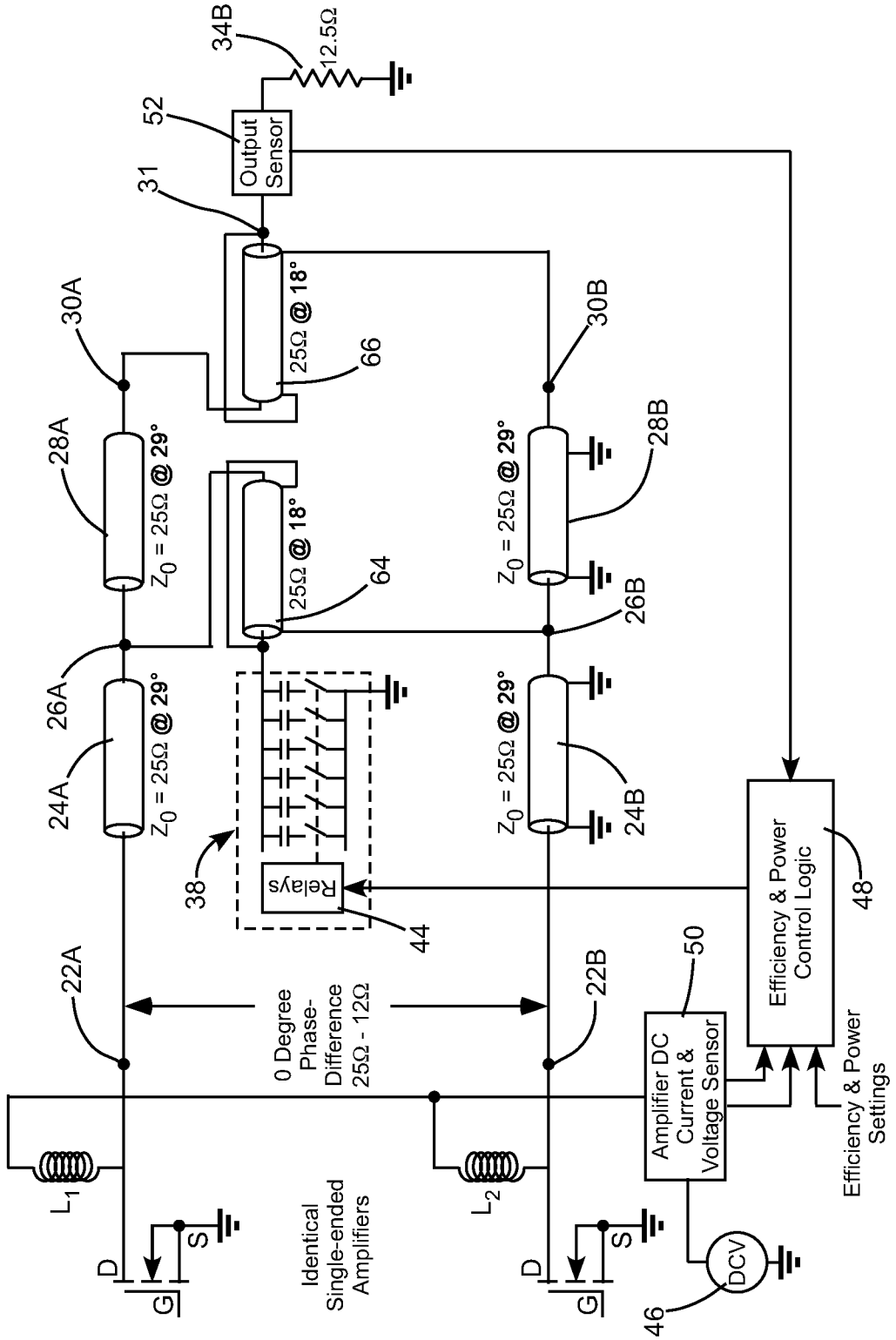

34B
12.5Ω
52
Output Sensor
31
30A
30B
28A
28B
66
25Ω @ 18°
64
Z_0 = 25Ω @ 29°
26A
26B
24A
24B
38
Relays
44
22A
22B
0 Degree Phase-Difference 25Ω - 12Ω
50
Amplifier DC Current & Voltage Sensor
Efficiency & Power Control Logic
48
Efficiency & Power Settings
L_1
L_2
D
G
S
Identical Single-ended Amplifiers
DCV
46
60B

FIG. 7

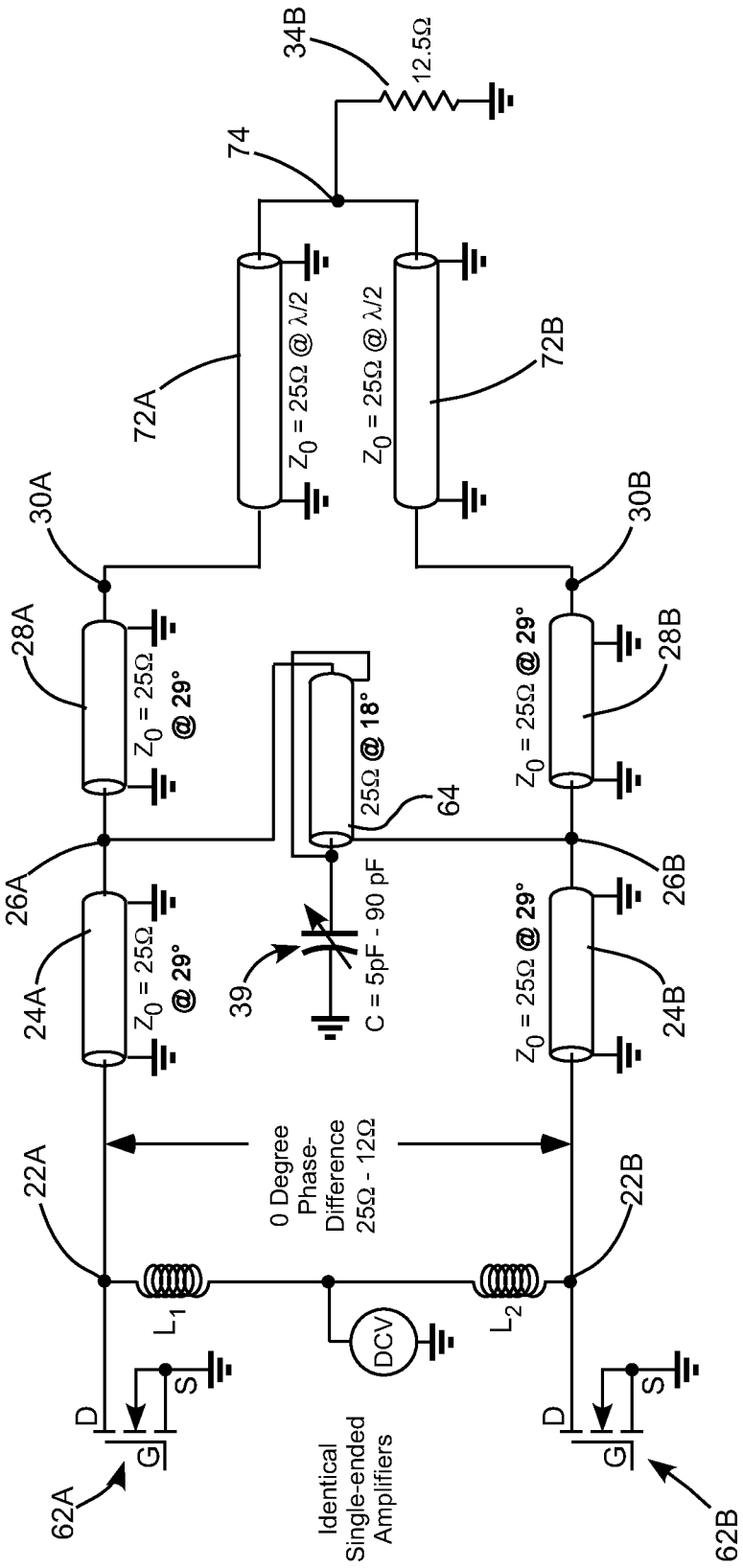

34B
12.5Ω
74
72A
72B
Z_0 = 25Ω @ λ/2
Z_0 = 25Ω @ λ/2
30A
30B
70
28A
28B
Z_0 = 25Ω @ 29°
Z_0 = 25Ω @ 29°
25Ω @ 18°
64
26A
26B
24A
24B
Z_0 = 25Ω @ 29°
Z_0 = 25Ω @ 29°
39
C = 5pF - 90 pF
0 Degree Phase-Difference 25Ω - 12Ω
22A
22B
L_1
L_2
DCV
D
G
S
D
G
S
62A
62B
Identical Single-ended Amplifiers

FIG. 8

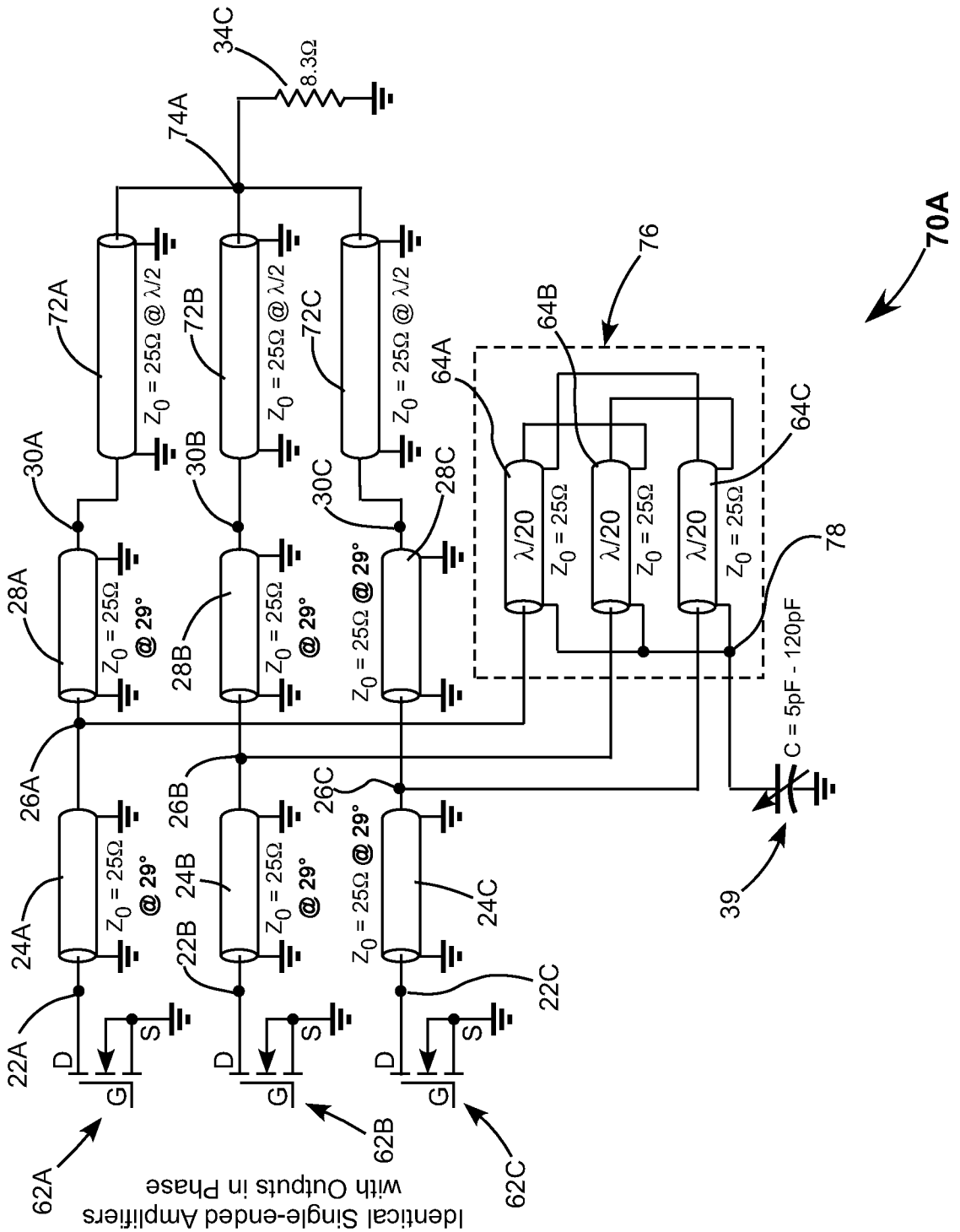

70A
76
64A
64B
64C
72A
72B
72C
74A
34C
8.3Ω
30A
30B
30C
28A
28B
28C
26A
26B
26C
24A
24B
24C
22A
22B
22C
62A
62B
62C
39
78
C = 5pF - 120pF
λ/20
Z0 = 25Ω
Z0 = 25Ω @ λ/2
Z0 = 25Ω @ 29°
D
G
S
Identical Single-ended Amplifiers
with Outputs in Phase

FIG. 9

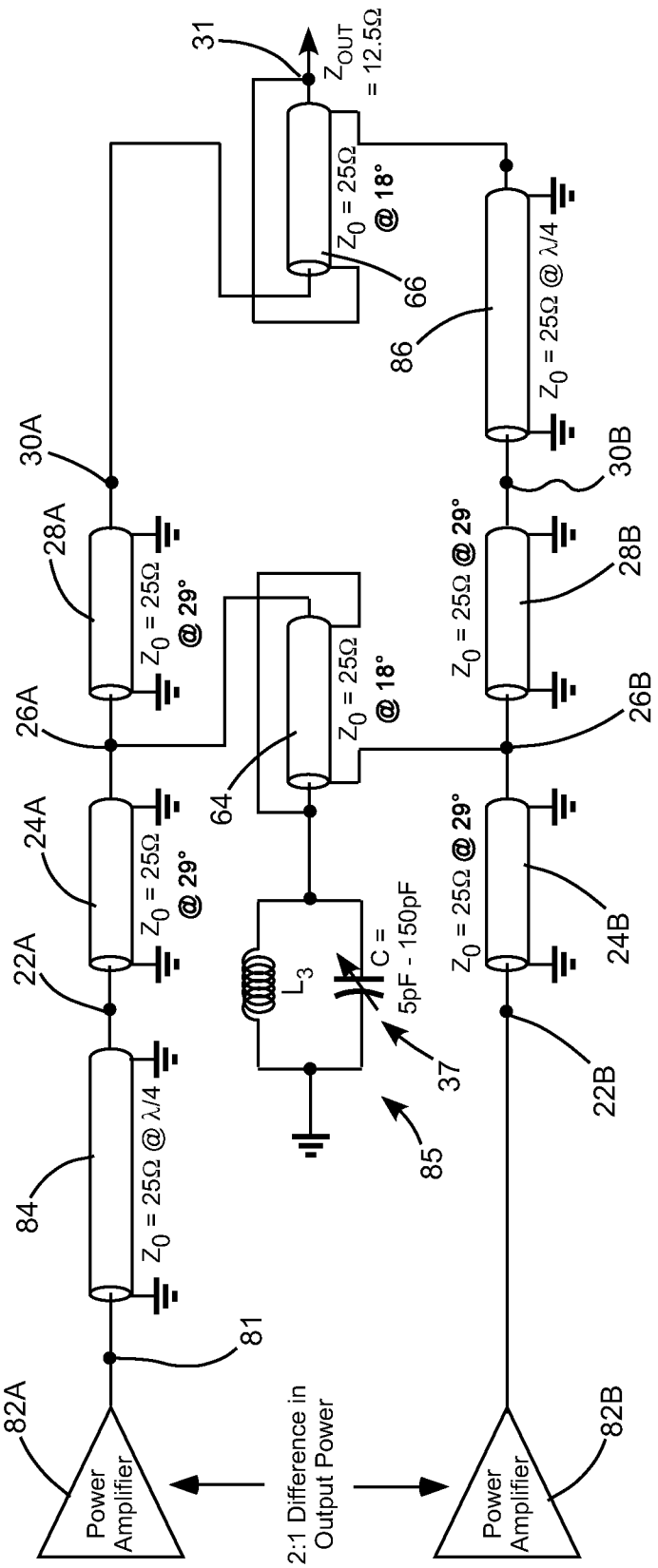

80
31
Z_{OUT} = 12.5Ω
Z_0 = 25Ω @ 18°
66
86
Z_0 = 25Ω @ λ/4
30A
30B
28A
28B
Z_0 = 25Ω @ 29°
26A
26B
64
Z_0 = 25Ω @ 18°
24A
24B
22A
22B
L_3
C = 5pF - 150pF
37
85
84
81
82A
82B
Power Amplifier
2:1 Difference in Output Power

FIG. 10

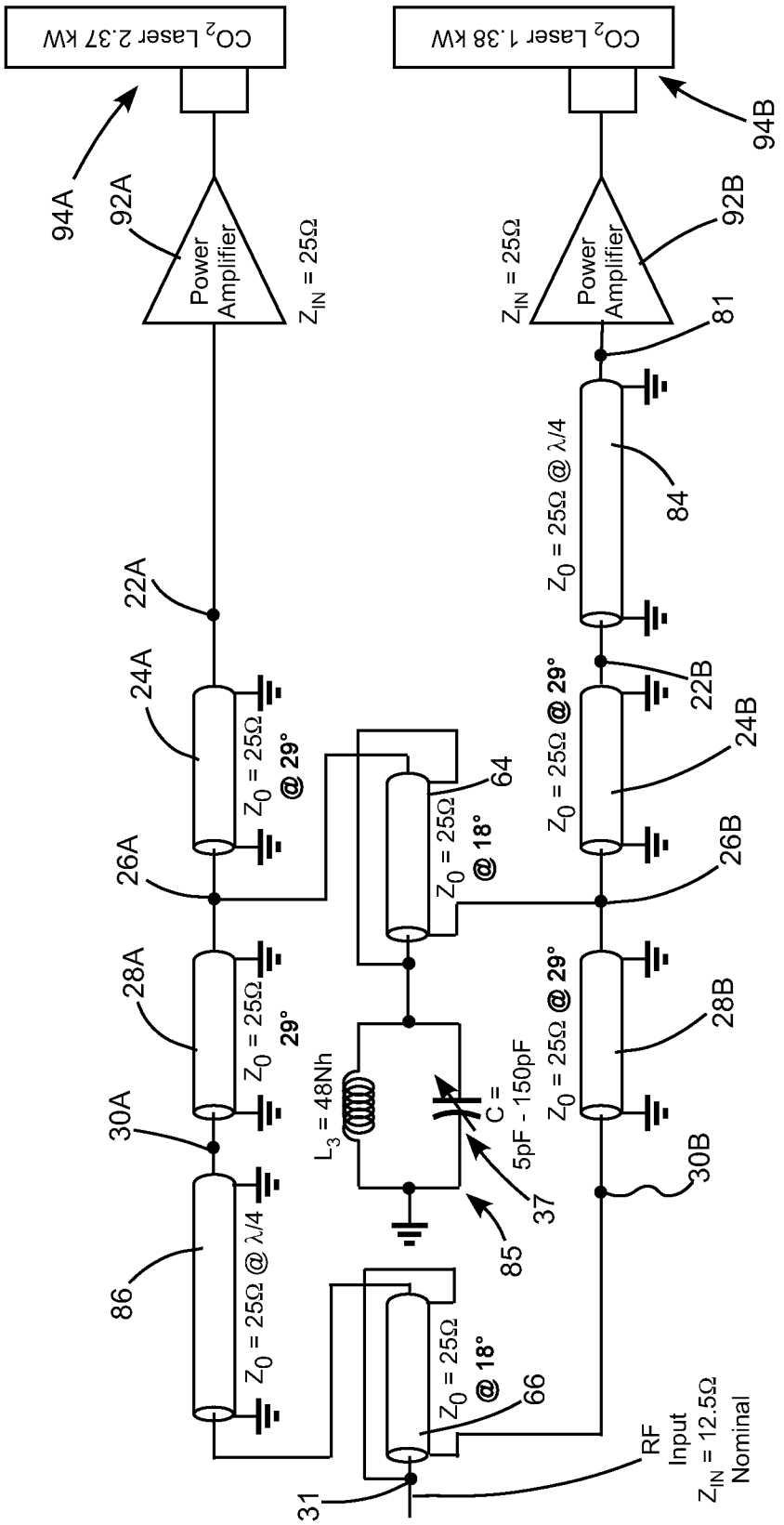

CO2 Laser 2.37 kW
CO2 Laser 1.38 kW
94A
94B
92A
92B
Power Amplifier
Power Amplifier
ZIN = 25Ω
ZIN = 25Ω
81
22A
22B
24A
24B
26A
26B
28A
28B
30A
30B
84
86
64
66
85
37
31
Z0 = 25Ω @ 29°
Z0 = 25Ω @ λ/4
Z0 = 25Ω @ 18°
L3 = 48Nh
C = 5pF - 150pF
RF Input ZIN = 12.5Ω Nominal
90

FIG. 11

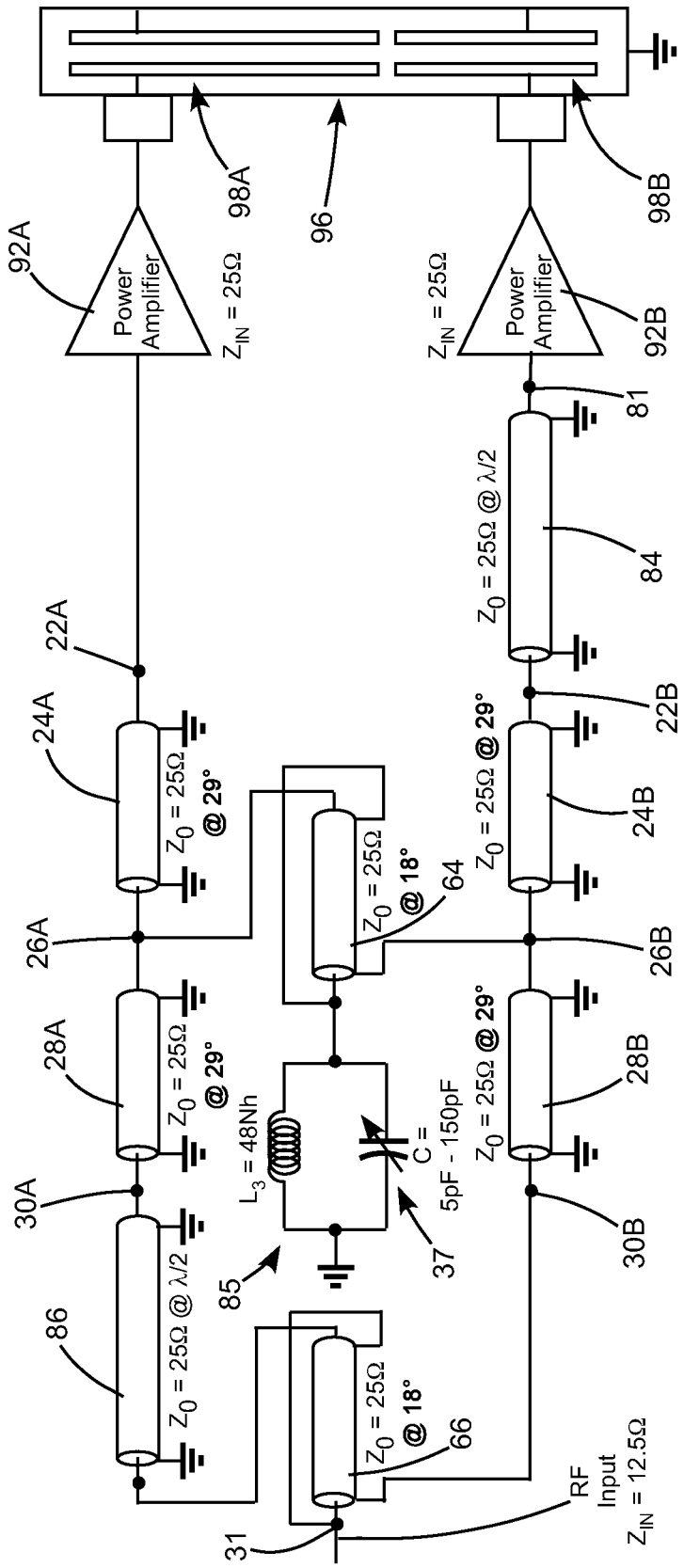

92A
Power Amplifier
Z_{IN} = 25Ω
98A
96
98B
92B
Power Amplifier
Z_{IN} = 25Ω
81
90A
22A
24A
Z_0 = 25Ω @ 29°
26A
28A
Z_0 = 25Ω @ 29°
30A
Z_0 = 25Ω @ λ/2
86
L_3 = 48Nh
C = 5pF - 150pF
85
37
Z_0 = 25Ω @ 18°
64
66
31
RF Input
Z_{IN} = 12.5Ω
Z_0 = 25Ω @ λ/2
84
22B
Z_0 = 25Ω @ 29°
24B
26B
Z_0 = 25Ω @ 29°
28B
30B

FIG. 11A

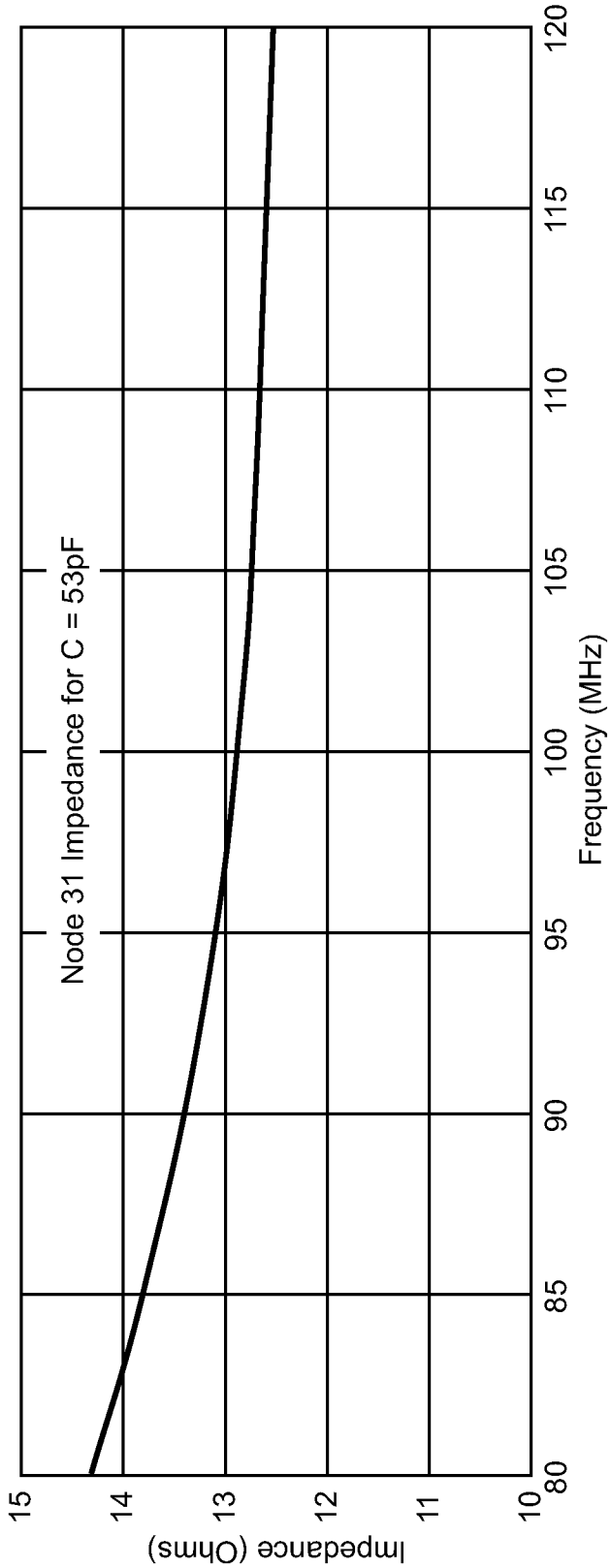

Node 31 Impedance for C = 53pF
Impedance (Ohms)
15
14
13
12
11
10
80
85
90
95
100
105
110
115
120
Frequency (MHz)

FIG. 12

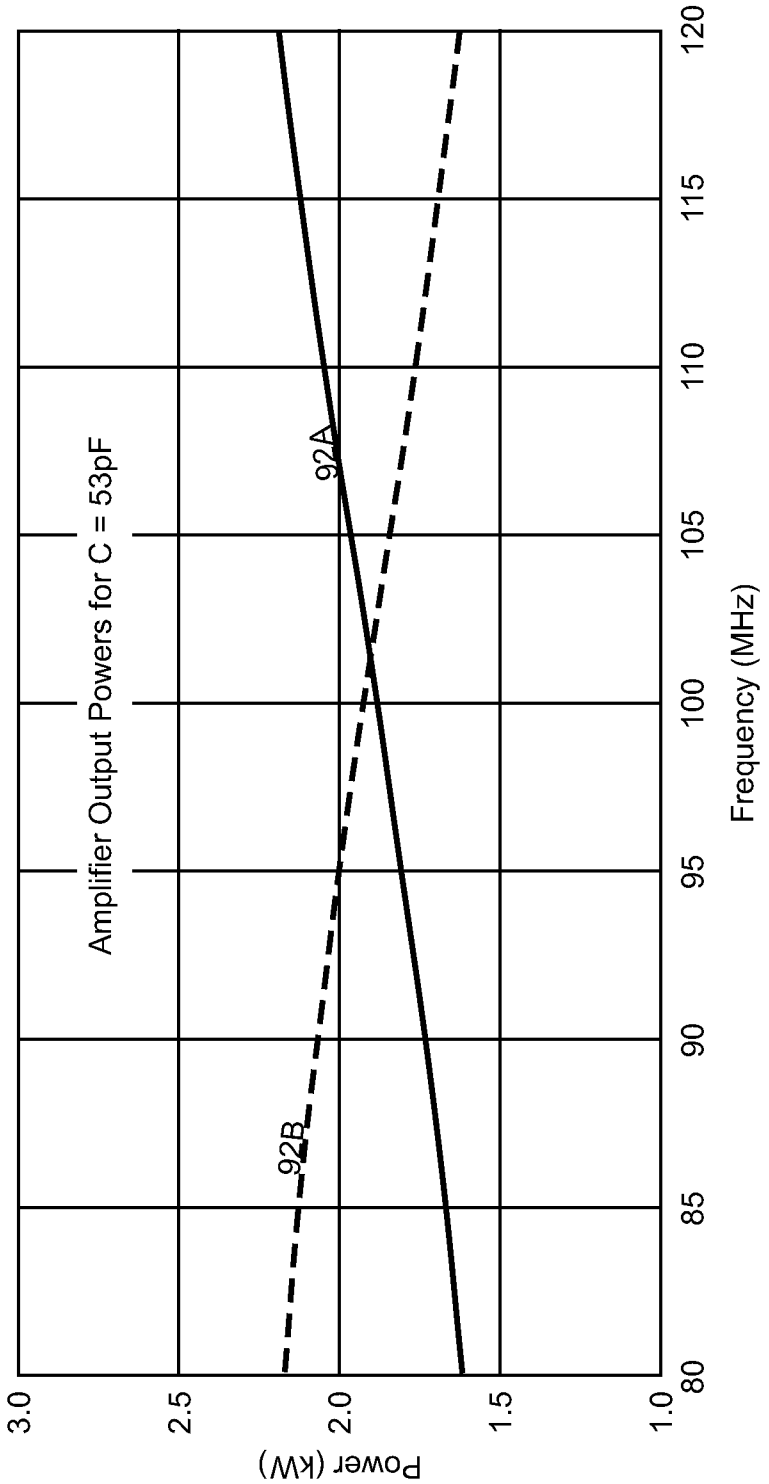

Amplifier Output Powers for C = 53pF
92A
92B
Power (kW)
3.0
2.5
2.0
1.5
1.0
80
85
90
95
100
105
110
115
120
Frequency (MHz)

FIG. 13

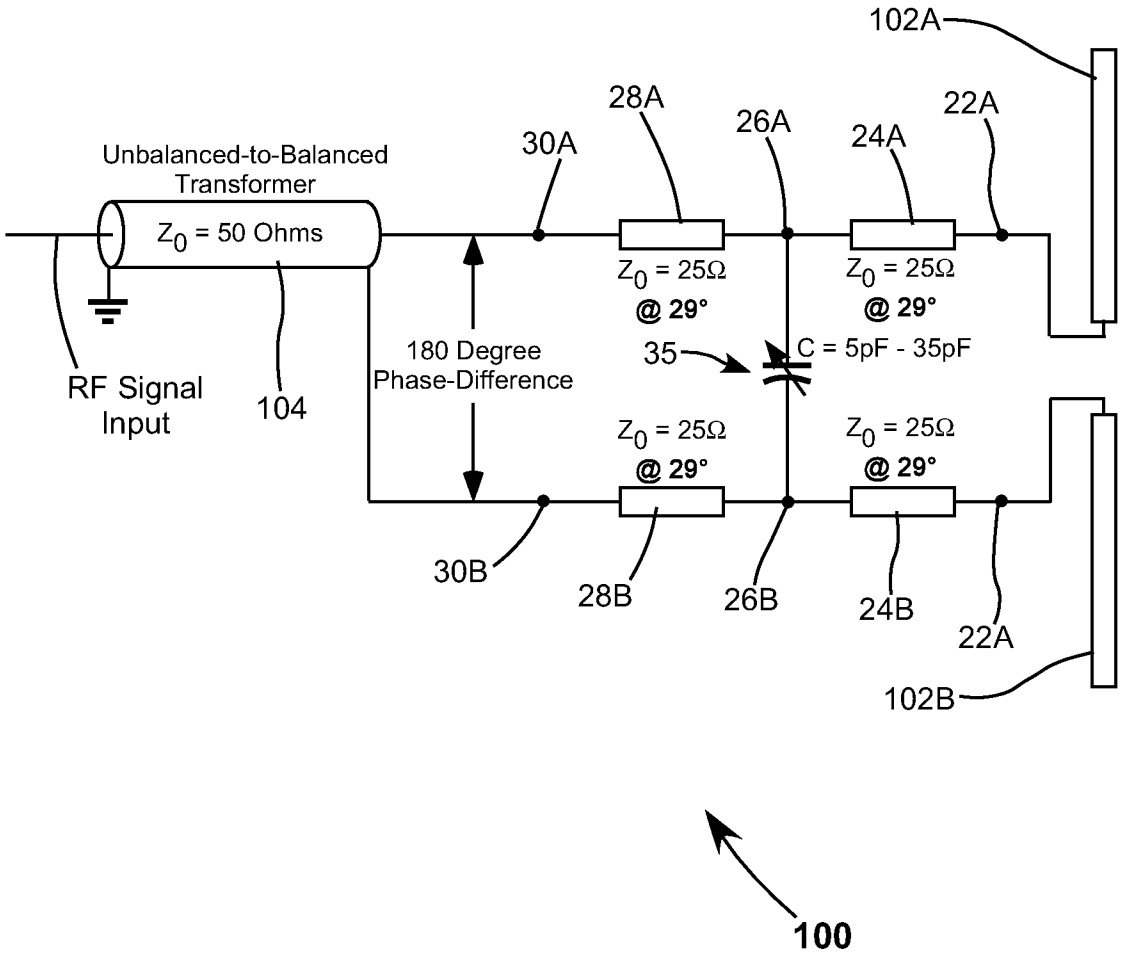

102A
28A
26A
22A
30A
24A
Unbalanced-to-Balanced
Transformer
Z_0 = 50 Ohms
Z_0 = 25Ω
@ 29°
Z_0 = 25Ω
@ 29°
180 Degree
Phase-Difference
35
C = 5pF - 35pF
RF Signal
Input
104
Z_0 = 25Ω
@ 29°
Z_0 = 25Ω
@ 29°
30B
28B
26B
24B
22A
102B
100

FIG. 14

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/052740

A. CLASSIFICATION OF SUBJECT MATTER
INV. H03H7/38 H03H7/42 H03H7/48 H01Q1/00 H03F1/56
H03F3/45 H03F3/60
ADD.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H03H H01Q H03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 939 980 A1 (BROADCOM CORP [US]) 2 July 2008 (2008-07-02)	1-5,19, 20
A	paragraphs [0168] - [0173]; figure 43	6-18

Y	EP 0 418 538 A1 (MOTOROLA SEMICONDUCTEURS BORDE [FR] MOTOROLA SEMICONDUCTEURS [FR]) 27 March 1991 (1991-03-27)	1-5
A	figure 4	19,20

Y	US 5 008 894 A (LAAKMANN PETER [US]) 16 April 1991 (1991-04-16)	1-5
A	figures 2,5	17,18

Y	WO 2009/060213 A1 (MICROONCOLOGY LTD [GB]; HANCOCK CHRISTOPHER PAUL [GB]) 14 May 2009 (2009-05-14)	1-5
A	page 58, line 1 - page 61, line 35; figures 4a,4b	17,18

	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

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Date of the actual completion of the international search	Date of mailing of the international search report
19 January 2012	31/01/2012

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Naumann, Olaf

2

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/052740

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 771 026 A (STENGEL JR FRANCIS A [US]) 23 June 1998 (1998-06-23) figure 7	1-5,19, 20
A	US 4 806 944 A (JACOMB-HOOD ANTHONY W [US]) 21 February 1989 (1989-02-21) figure 7	1,3,14, 19
A	DARREL EMERSON: "The Twelfth-Wave Matching Transformer", QST, AMERICAN RADIO RELAY LEAGUE, NEWINGTON, CT, US, vol. 81, no. 6, 1 June 1997 (1997-06-01), pages 43-44, XP009151152, ISSN: 0033-4812 the whole document	1,14,19
Y	FUKUDA A ET AL: "A 900/1500/2000-mhz triple-band reconfigurable power amplifier employing RF-MEMs switches", 2005 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM, PISCATAWAY, NJ, USA,IEEE, 12 June 2005 (2005-06-12), pages 657-660, XP010844550, DOI: 10.1109/MWSYM.2005.1516691 ISBN: 978-0-7803-8846-8	1-5
A	figures 1-3	19,20

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2011/052740

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 1939980 A1	02-07-2008	CN 101232311 A	30-07-2008
		EP 1939980 A1	02-07-2008
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