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(54) **SUSPENDED TRANSMISSION LINE WITH EMBEDDED AMPLIFIER**

(75) Inventors: **James R. Sherman**, Seminole, FL (US); **Ofira M. Von Stein**, Madeira Beach, FL (US)

(73) Assignee: **Raytheon Company**, Lexington, MA (US)

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(52) **U.S. Cl.** **330/286**; 330/53; 330/65; 333/238; 333/246

(58) **Field of Search** 330/53, 54, 65–68, 330/286; 333/238, 246

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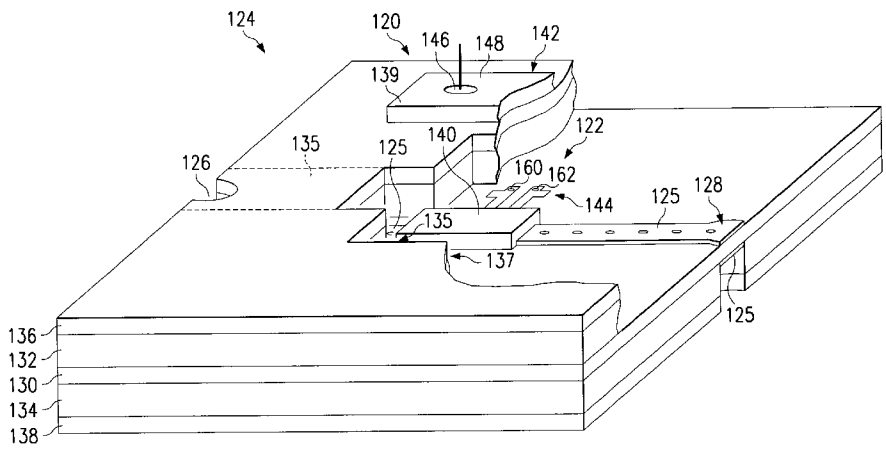
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Primary Examiner—Patricia T. Nguyen
(74) *Attorney, Agent, or Firm*—Baker Botts L.L.P.

(57) **ABSTRACT**

A suspended transmission line with an embedded amplifier includes a support layer and a conductor supported on the support layer between first and second plates each having a ground plane. The conductor includes an input section and an output section. A propagation structure is disposed between the first and second plates to substantially encompass an electric field generated by a signal transmitted on the conductor. An amplifier is coupled to the input and output sections of the conductor and is at least substantially disposed between the first and second plates. The amplifier operates to amplify an input signal received on the input section to generate an output signal on the output section.

28 Claims, 7 Drawing Sheets



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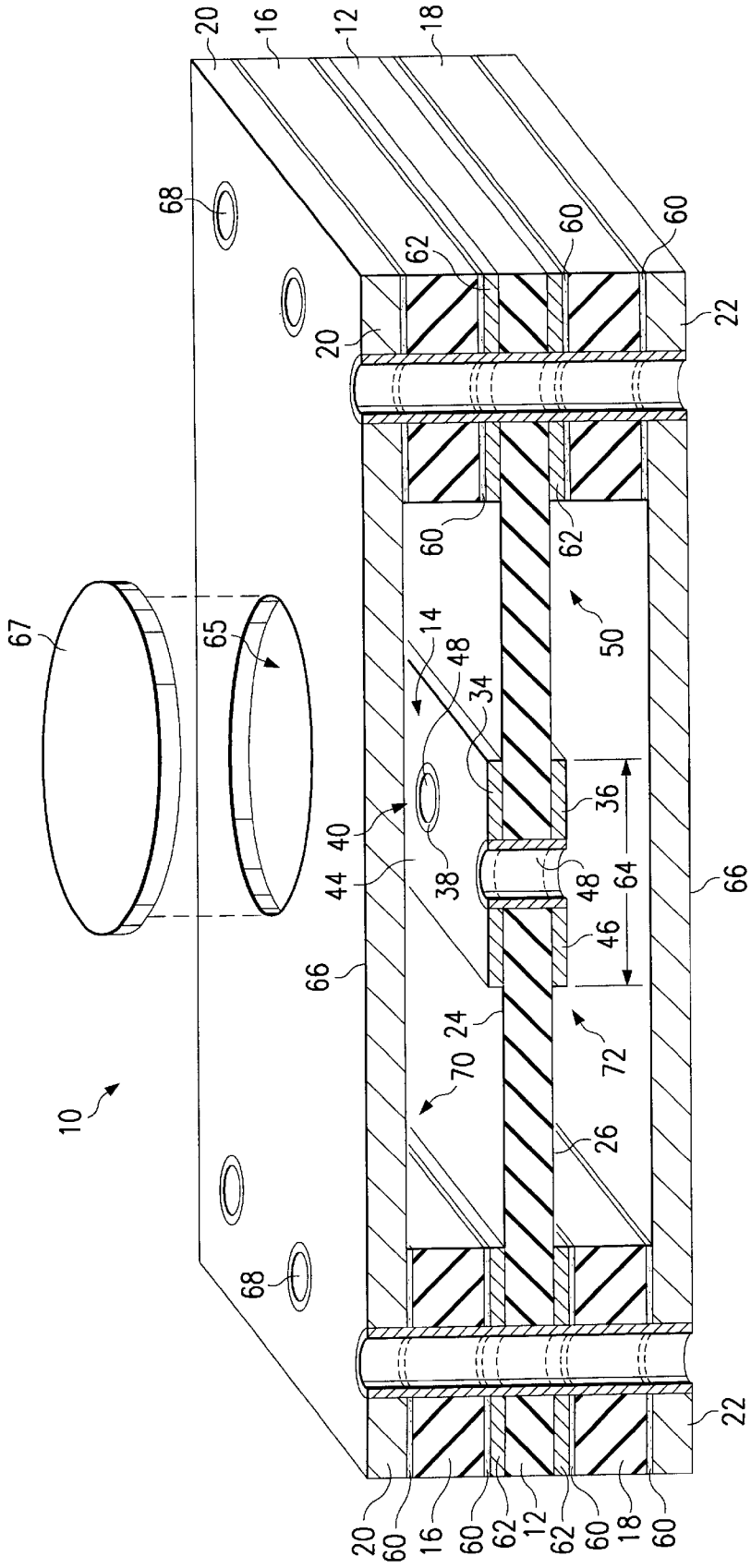

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FIG. 1

FIG. 2

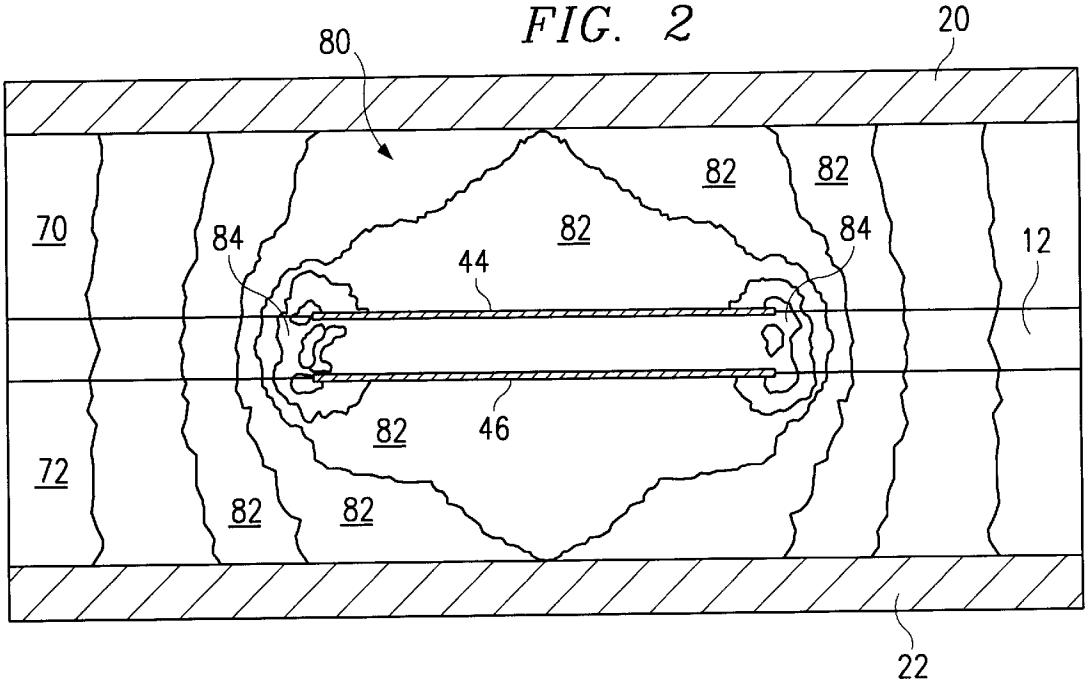


FIG. 3

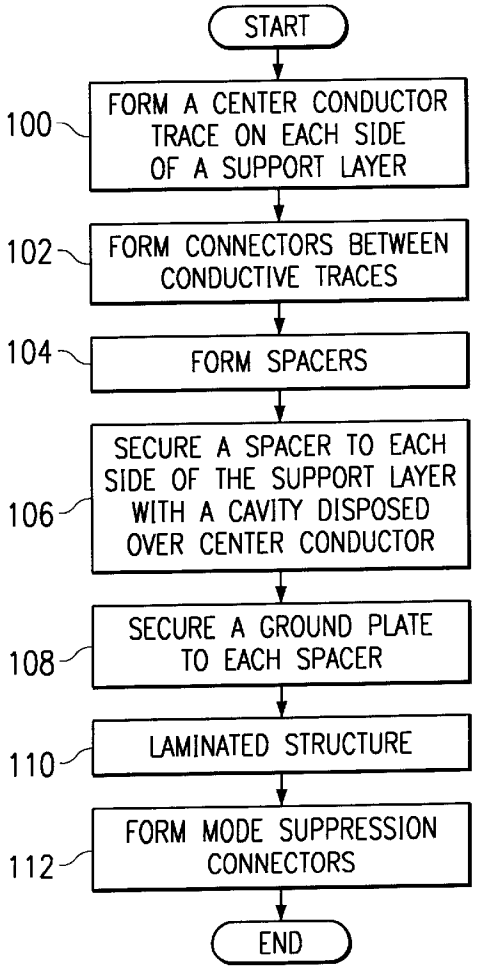


FIG. 4

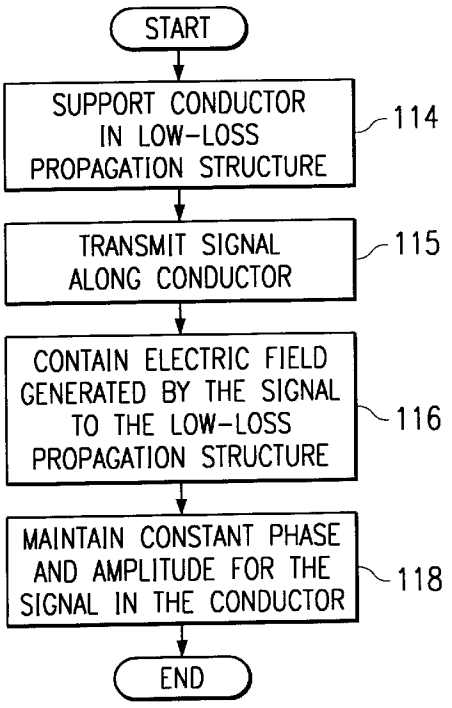


FIG. 5

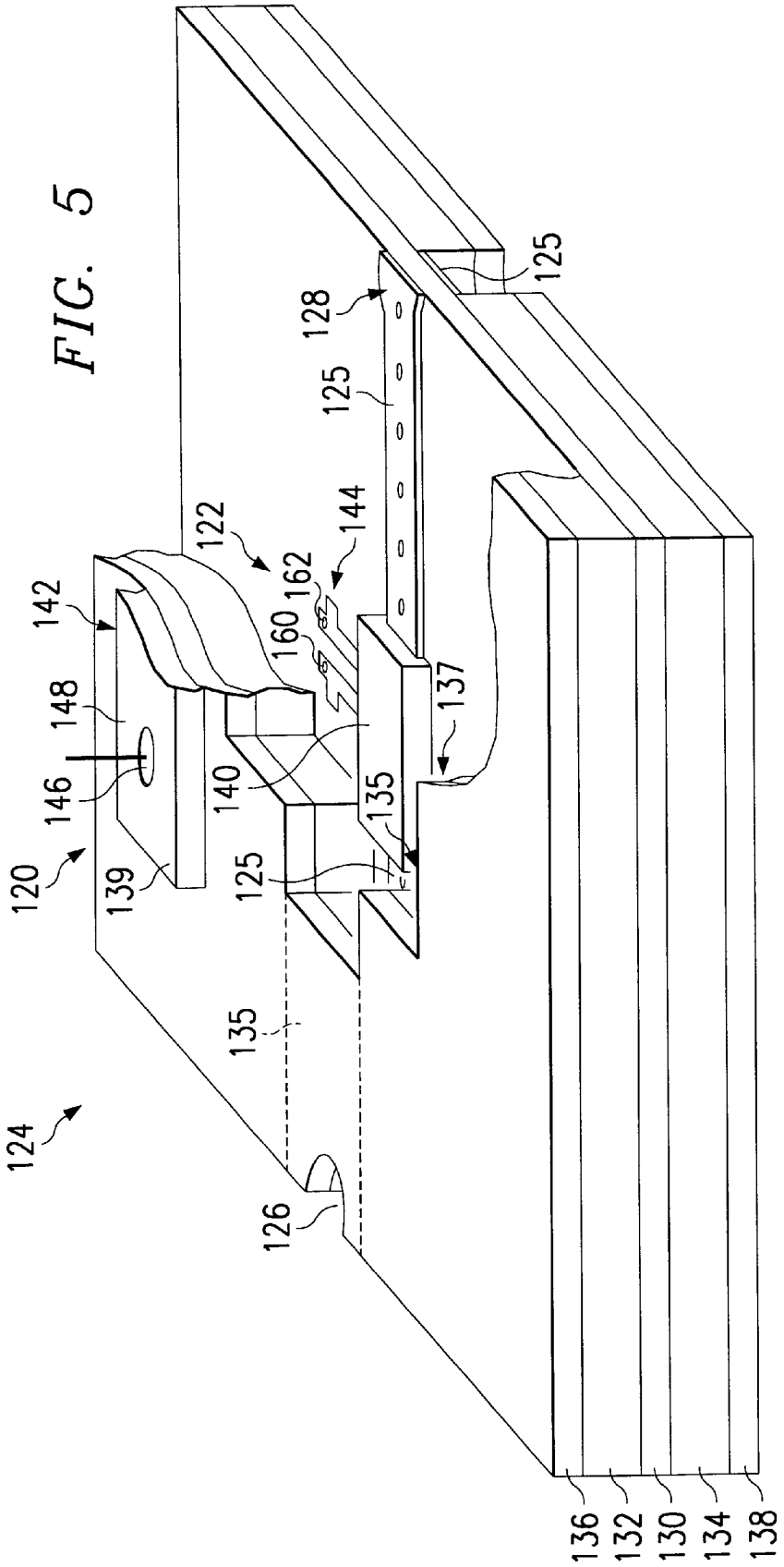

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FIG. 6

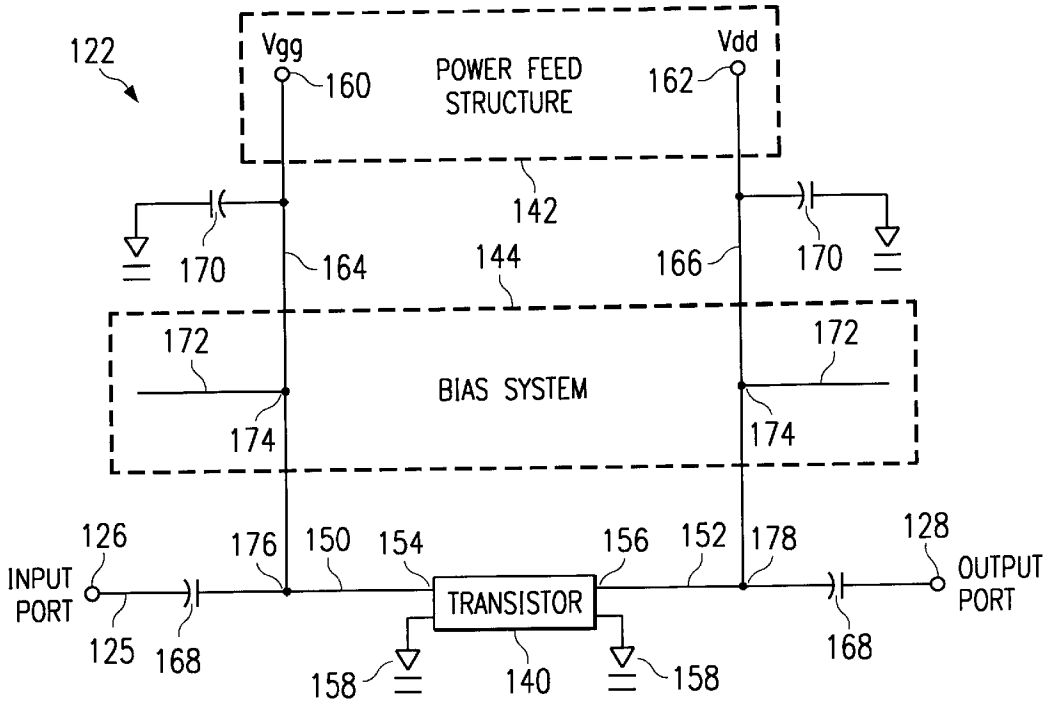

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POWER FEED STRUCTURE
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BIAS SYSTEM
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INPUT PORT
OUTPUT PORT
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FIG. 7A

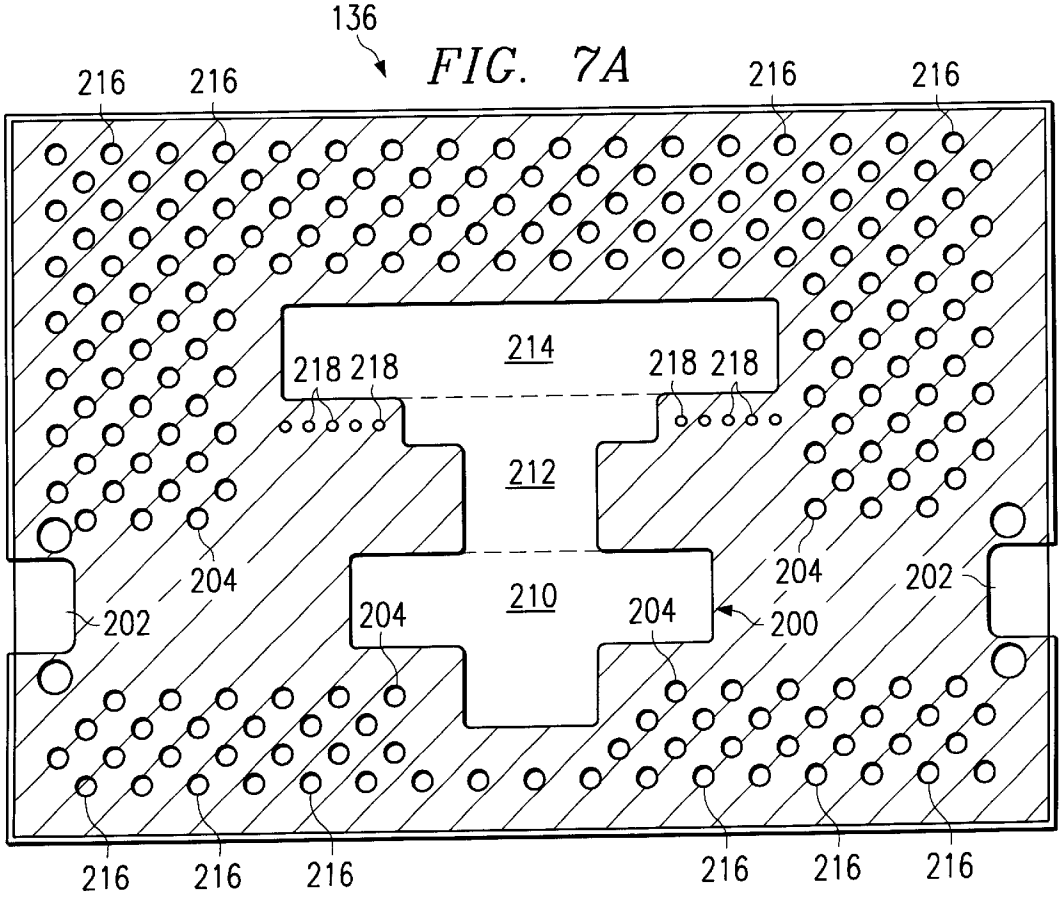

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FIG. 7B

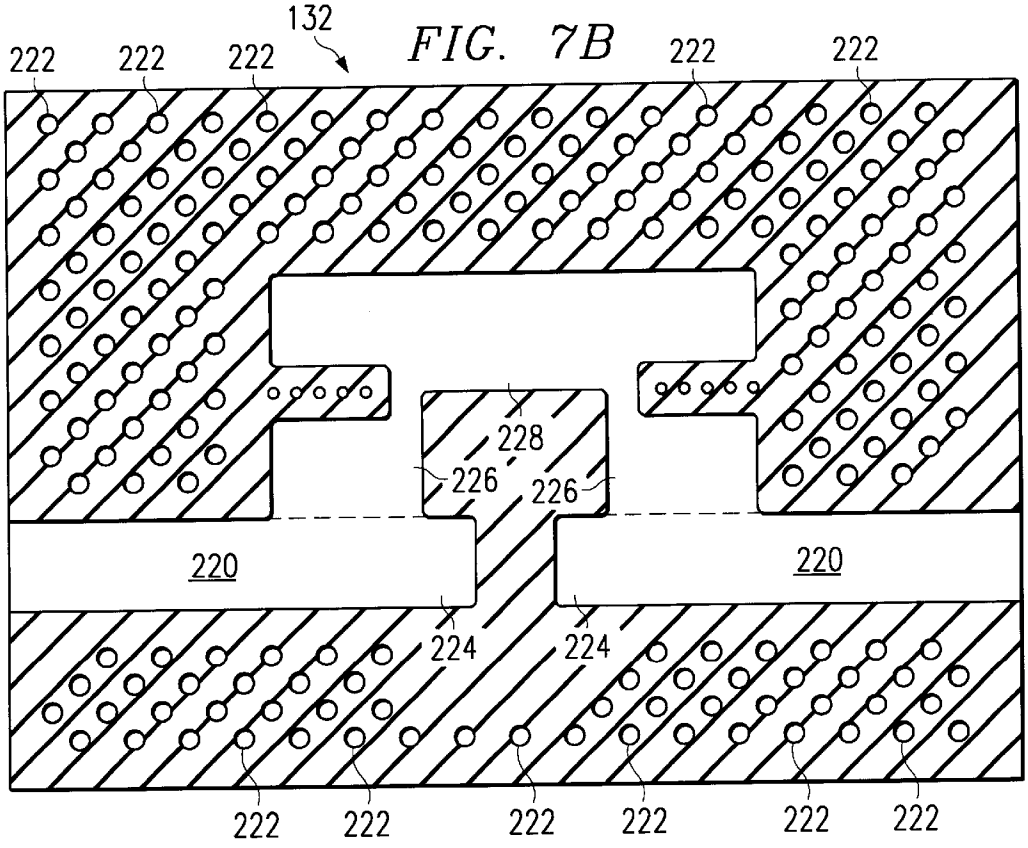

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FIG. 7C

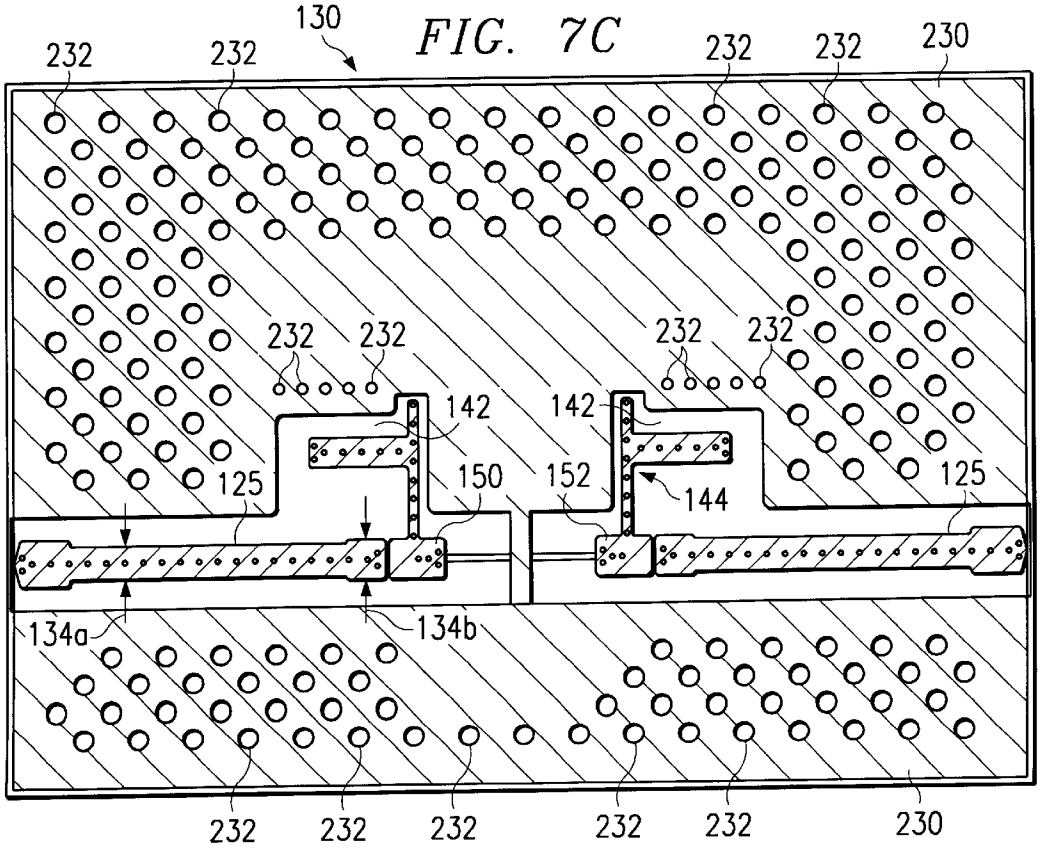

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FIG. 7D

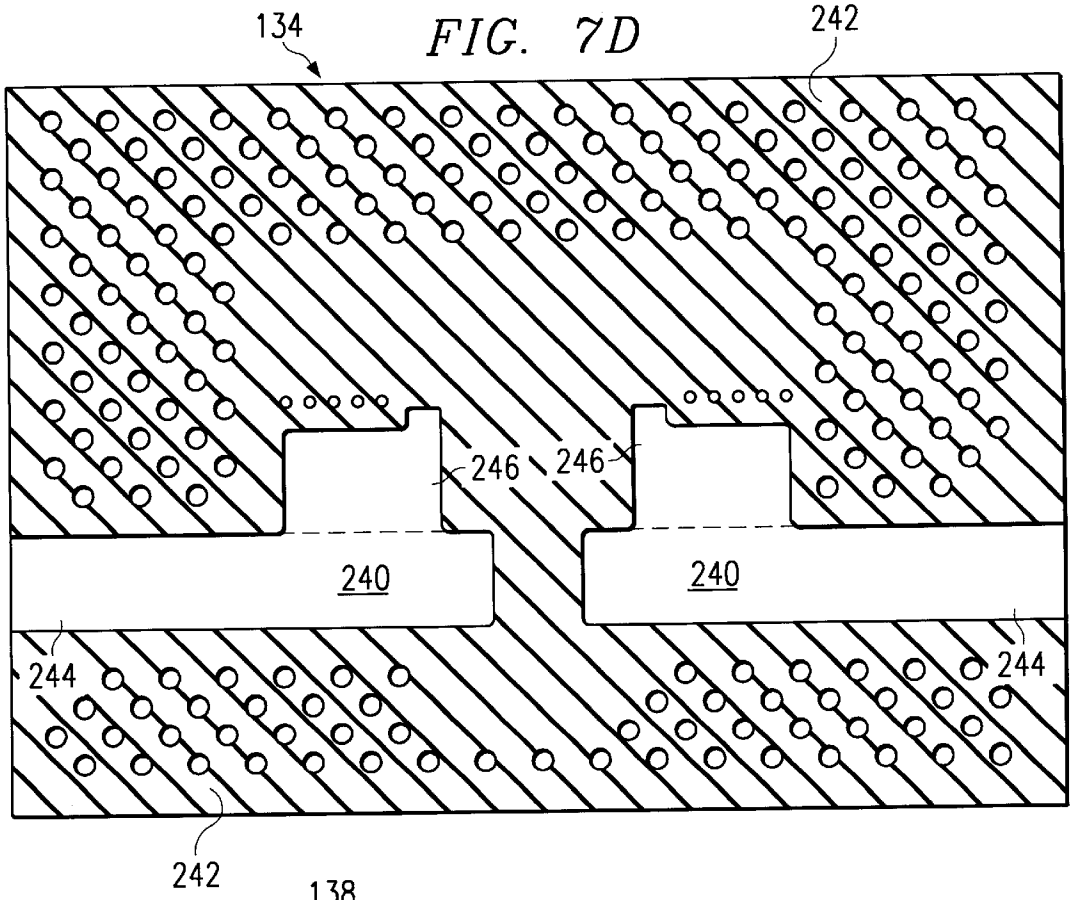

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FIG. 7E

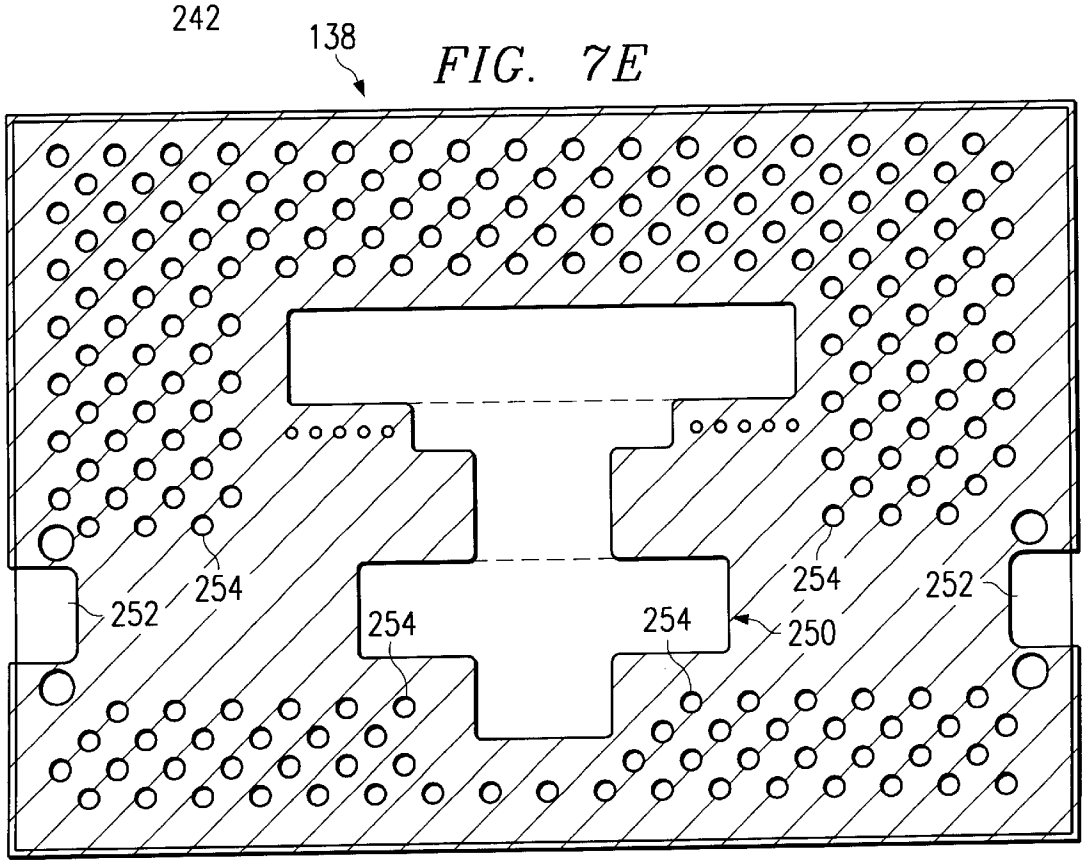

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FIG. 7F

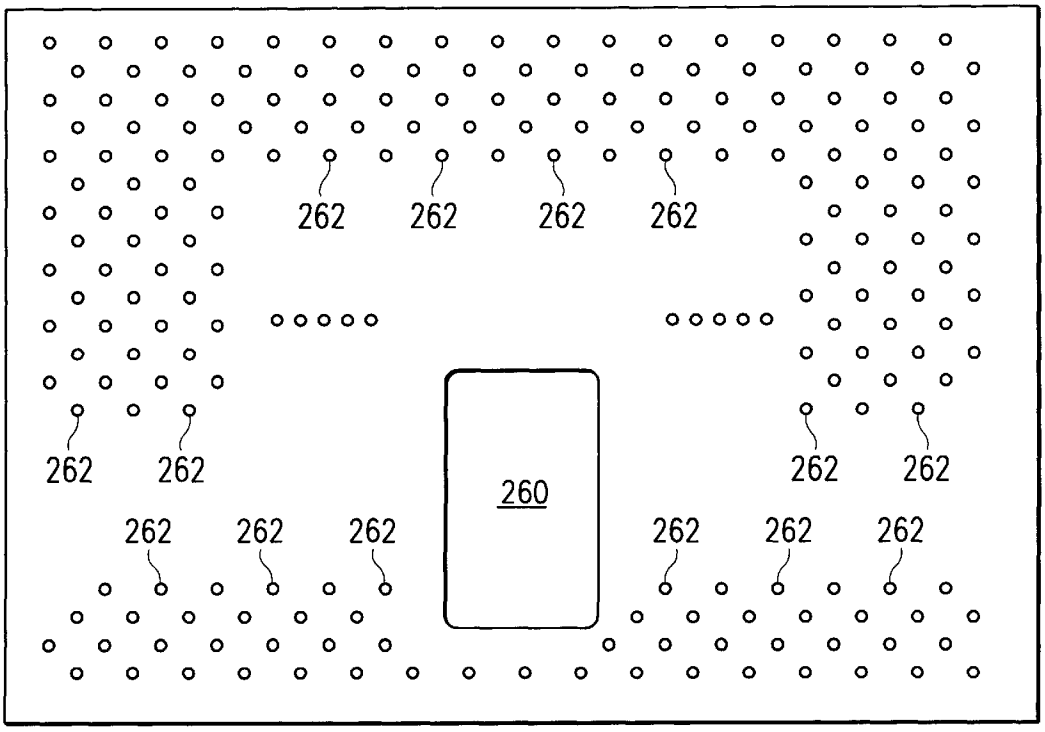
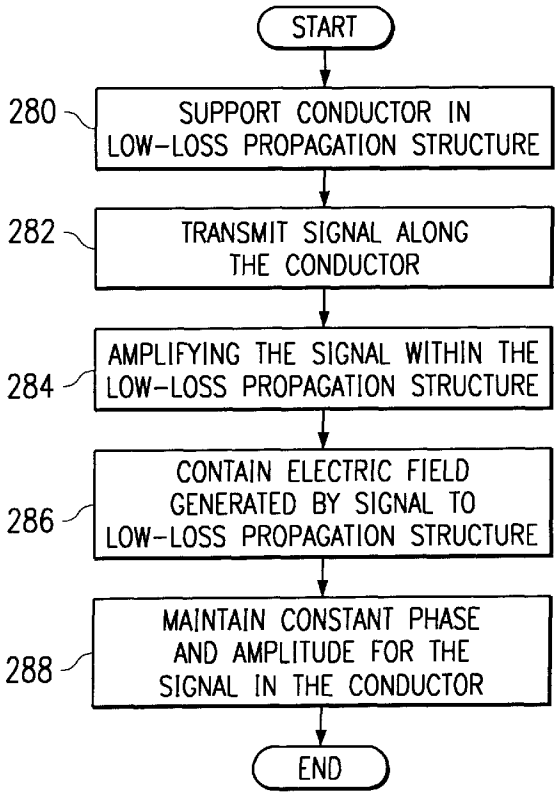

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FIG. 8


START
280
SUPPORT CONDUCTOR IN LOW-LOSS PROPAGATION STRUCTURE
282
TRANSMIT SIGNAL ALONG THE CONDUCTOR
284
AMPLIFYING THE SIGNAL WITHIN THE LOW-LOSS PROPAGATION STRUCTURE
286
CONTAIN ELECTRIC FIELD GENERATED BY SIGNAL TO LOW-LOSS PROPAGATION STRUCTURE
288
MAINTAIN CONSTANT PHASE AND AMPLITUDE FOR THE SIGNAL IN THE CONDUCTOR
END

SUSPENDED TRANSMISSION LINE WITH EMBEDDED AMPLIFIER

RELATED APPLICATIONS

This application is related to U.S. patent application Ser. No. 09/548,691 entitled "Suspended Transmission Line and Method", U.S. patent application Ser. No. 09/548,686 entitled "Suspended Transmission Line with Embedded Signal Channeling Device", U.S. patent application Ser. No. 09/548,578 entitled "Integrated Broadside Conductor for Suspended Transmission Line and Method", and U.S. application Ser. No. 09/548,689 entitled "Method for Fabricating Suspended Transmission Line", all filed on Apr. 13, 2000.

TECHNICAL FIELD OF THE INVENTION

This invention relates generally to the field of signal transmission systems, and more particularly to a suspended transmission line with an embedded amplifier.

BACKGROUND OF THE INVENTION

Microwave and radio frequency circuits are generally implemented by interconnecting amplifiers, antennas, transmitters, receivers, and other components by a series of transmission lines. The transmission lines propagate microwave and radio frequency energy between the components of the circuit.

Transmission lines are generally implemented as waveguide pipes, striplines, and/or coaxial cables. Waveguide pipes are often impractical, however, because of the difficulty of installation and the size and weight is excessive for many applications. Striplines and coaxial cables are more compact and easier to install, but use special materials and fabrication processes that lead to high transmission line cost.

Further adding to the expense of microwave and radio frequency circuits is the expense of implementing amplifiers, antennas, and other components within the circuit. Typically, each component is implemented in a specially fabricated mechanical housing such as an aluminum box having signal, digital, and power connectors. These mechanical housings must generally be designed, engineered, and machined with tight tolerances for microwave and other high frequency applications. In addition, drawing packages need to be generated and maintained for each housing. Connectors must also be thermally matched to the mechanical housing.

SUMMARY OF THE INVENTION

The present invention provides a transmission line amplifier that substantially eliminates or reduces the problems and disadvantages associated with prior methods and systems. In particular, the amplifier is embedded into a suspended transmission line for use in microwave and radio frequency applications.

In accordance with one embodiment of the present invention, a suspended transmission line with an embedded amplifier includes a support layer and a conductor supported on the support layer between first and second plates each having a ground plane. The conductor includes an input section and an output section. A propagation structure is positioned between the first and second plates to substantially contain an electric field generated by a signal transmitted on the conductor. An amplifier is coupled to the input and output sections of the conductor and is at least substantially disposed between the first and second plates. The amplifier operates to amplify an input signal received on the input section to generate an output signal on the output section.

Technical advantages of the present invention include providing a low cost and space efficient transmission system. In particular, amplifiers and other elements are embedded into the transmission line substantially without degradation in line performance. The amplifiers may be low noise and power amplifiers. Other embedded elements may be high power broadband combiners, filters, diplexers, and other passive elements as well as mixers, multipliers, switches, and other active elements. As a result, the transmission line structure is self-contained and includes fewer parts. The cost of designing, engineering, constructing, and maintaining separate mechanical housings for each element is minimized.

Another technical advantage of the present invention includes providing an improved power amplifier structure for microwave and radio frequency applications. In particular, the power amplifier is embedded within and integral with a suspended transmission line. As a result, separate substrates and carriers for the amplifier are eliminated. Separate transmission line connectors for the amplifier are also eliminated. Thus, the power amplifier may be constructed at relatively low cost.

Other technical advantages of the present invention will be readily apparent to one skilled in the art from the following figures, description, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and its advantages, reference is now made to the following description taken in conjunction with the accompanying drawings, wherein like reference numerals represent like parts, in which:

FIG. **1** is a sectional diagram illustrating a suspended transmission line in accordance with one embodiment of the present invention;

FIG. **2** is a sectional diagram illustrating distribution of an electric field in the suspended transmission line of FIG. **1**;

FIG. **3** is a flow diagram illustrating a method for fabricating the suspended transmission line of FIG. **1** in accordance with one embodiment of the present invention;

FIG. **4** is a flow diagram illustrating a method for transmitting a signal in the transmission line of FIG. **1** in accordance with one embodiment of the present invention;

FIG. **5** is a perspective diagram illustrating a power amplifier embedded into a suspended transmission line in accordance with one embodiment of the present invention;

FIG. **6** is a schematic diagram illustrating the configuration of the center connector for the embedded power amplifier of FIG. **5** in accordance with one embodiment of the present invention;

FIGS. **7**A–F are top plan diagrams illustrating the configuration of each layer for the embedded power amplifier of FIG. **5** in accordance with one embodiment of the present invention; and

FIG. **8** is a flow diagram illustrating a method for amplifying a signal in a suspended transmission line in accordance with one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **1** illustrates a suspended transmission line **10** in accordance with one embodiment of the present invention.

In this embodiment, the suspended transmission line **10** is used to transmit microwave and other radio frequency signals in a transmission system. The transmitted signal may be an outgoing signal being transmitted to an antenna or an incoming signal being received from an antenna. As described in more detail below, an amplifier, power divider, or other active or passive device may be embedded into the transmission line **10** to manipulate a transmitted signal. It will be understood that the suspended transmission line **10** may be otherwise suitably configured for use in microwave, radio frequency and other suitable high power or other applications.

Referring to FIG. **1**, the suspended transmission line **10** includes a support layer **12** supporting a center conductor **14**, first and second spacers **16** and **18** each disposed on opposite sides of the support layer **12**, and first and second plates **20** and **22** each disposed outwardly of a corresponding spacer **16** or **18**. As described in more detail below, each of the layers **12**, **16**, **18**, **20**, and **22** may be separately fabricated and thereafter laminated together to form the suspended transmission line **10**.

The support layer **12** is a thin dielectric sheet having a first side **24** and an opposite second side **26**. The thickness of the support layer **12** is preferably minimized to a thickness needed to support the center conductor **14** in order to minimize the cross section of the support layer **12** and thus limit electrical fields in the layer **12**. The support layer **12** may be continuous or include openings (not shown) to control propagation characteristics of the suspended transmission line **10**, to allow integration of components directly into the suspended transmission line **10**, and the like.

The support layer **12** is fabricated from a lossy or other inexpensive dielectric material. The use of a lossy dielectric material for the support layer **12** avoids the necessity of exotic low-loss materials such as Alumina, Duroid, cross-linked polystyrene, and Beryllium Oxide previously used to support a conductor in a suspended transmission line. Although such low-loss materials improve performance, such materials are typically very expensive. A lossy material is the material of preference because, as described in more detail below, the center conductor **14** is configured to direct an electric field generated by a signal on the center conductor **14** substantially away from the support layer **12** such that only fringing electrical fields cross the support layer **12**. Dissipation losses due to the fringing electrical fields are minimal even in the lossy material of the support layer **12**. As a result, the suspended transmission line **10** may be produced at relatively low cost and used in high power and high performance applications.

The lossy material of the support layer **12** is an epoxy glass such as G-10 or GFG, polyimide glass, or other suitable printed circuit board base materials such as polyester, or other suitable lossy materials. A lossy material has a moderate loss tangent of about 0.04 or less. In one embodiment, G-10 material is preferred for the support layer **12** because G-10 has good dimensional stability over a large temperature range and is easy to laminate and match to other layers and materials. In another embodiment, an incremental increase in performance is obtained by using low loss PTFE material in place of the G-10 for the support layer **12**. Because the support layer **12** is thin, this results in only a small increase in cost.

The center conductor **14** is supported by the support layer **12** between the first and second plates **20** and **22**. The first and second plates **20** and **22** provide the upper and lower ground planes to the suspended transmission line **10**. The plates **20** and **22** may be solid metal or a base substrate material with metal layers on both sides. In one embodiment, the first and second plates **20** and **22** are solid copper to improve heat transfer. The center conductor **14** transmits a signal with low dissipation loss. Accordingly, the suspended transmission line **10** has utility to carry a signal directly between amplifiers, antennas, transmitters, receivers, and other components in the transmission or receiver system.

The center conductor **14** includes a first part **34** exposed at the first side **24** of the support layer and a second part **36** exposed at the second side **26** of the support layer **12**. The first and second parts **34** and **36** of the center conductor **14** preferably mirror each other to minimize in the support layer **12** the electric field generated by a signal transmitted on the center conductor **14**.

A third part **38** of the center conductor **14** connects the first and second parts **34** and **36** at intermediate points **40** along the length of the center conductor **14**. Connection of the first and second parts **34** and **36** at the intermediate points **40** produces equal phase and amplitude for a signal between the first and second parts **34** and **36** and reduces electric field coupling. As a result of this structure, the electric field generated by a transmitted signal is substantially directed away from the support layer **12** with only fringing electric fields in the support layer **12**. Further details of a typical electric field distribution are described below in connection with FIG. **2**.

Connection of the first and second parts **34** and **36** of the center conductor **14** at the intermediate points **40** means the first and second parts **34** and **36** are electrically connected to each other at least at spaced intervals along the length of the center conductor **14**. Spacing between the intermediate points **40** is substantially equal along the length of the center conductor **14** and is based on the frequency of the signal to be transmitted by the suspended transmission line **10**. In a particular embodiment, the center conductor **14** includes about 10 to 20 connections per wavelength of the transmitted signal frequency. It will be understood that other suitable spacing that maintains a substantially constant phase and amplitude for a signal on the center conductor **14** may be used.

In the illustrated embodiment, the center conductor **14** is an integrated broadside conductor. For this embodiment, the first part **34** of the center conductor **14** is a first conductive strip **44** disposed on the first side **24** of the support layer and the second part **36** of the center conductor **14** is a second conductive strip **46** disposed on the second side **26** of the support layer **12**. The first and second conductive strips **44** and **46** are silver-plated copper or other suitable metal traces that minimize conductor resistivity. The third part **38** of the center conductor **14** comprises a plurality of broadside connectors **48** each extending through the support layer **12** between the first and second conductive strips **44** and **46** to electrically couple the strips **44** and **46** at an intermediate point **40**. Unless otherwise specified, the use of the term each herein means each of at least a subset of the identified items. The connectors **48** are copper or silver-plated copper vias or other suitable conductive connectors.

The first and second spacers **16** and **18** maintain the plates **20** and **22** in space relation with the support layer **12**, and thus the center conductor **14**, to form a propagation structure **50** encompassing the center conductor **14** with air and ground planes for Quasi-TEM mode of propagation. The propagation structure **50** encompasses the center conductor **14** in that it is over, including above and/or below the

conductor **14** up to and not beyond the upper and lower ground plates **20** and **22**. As described in more detail below, the propagation structure **50** provides a low-loss medium for propagation of the electromagnetic field generated by a transmitted signal. Accordingly, dissipation losses are minimized along the suspended transmission line **10**.

The first and second spacers **16** and **18** may each be continuous along the propagation structure **50** or comprise a plurality of discrete posts or other suitable structures operable to maintain the plates **20** and **22** in space relation from the center conductor **14**. The spacers **16** and **18** are sized such that substantially all of the electromagnetic field generated by a transmitted signal on the center conductor **14** is maintained in the propagation structure **50**. Thus, as described in more detail below, spacer geometry is dependent on the transmitted signal frequency as well as the size, geometry, and materials of the support layer **12**, center conductor **14**, plates **20** and **22**, and propagation structure **50**.

The first and second spacers **16** and **18** are each fabricated of a dielectric, conductor, or other suitable material or materials. Preferably, the sidewalls of the spacers **16** and **18** are spaced apart and away from the center conductor **14** to minimize the effect on the electromagnetic field in the propagation structure **50**. This minimizes the changes in impedance along the direction of propagation. In addition, the spacer material preferably has a coefficient of thermal expansion equal or at least similar to the material of the support layer **12** so that the suspended transmission line **10** has good mechanical stability over a large temperature range. In a particular embodiment, the support layer **12** and spacers **16** and **18** are each fabricated of G-10 material and the plates **20** and **22** are fabricated of solid copper.

For the illustrated embodiment, each spacer **16** and **18** includes adhesion layers **60** at each edge for connecting the spacers to the support layer **12** and the plates **20** and **22**. The support layer **12** includes a metalization layer **62** on each side **24** and **26**. The metalization layers **62** form the point of attachment of the mode suppression connection vias **68**. These minimize the impedance altering effects of the potential higher order modes and reduce electromagnetic coupling between alternate board routes. In this embodiment, the first pacer **16** is attached to the metalization layer **62** on the first side **24** of the support layer **12** to separate the first plate **20** from the center conductor **14**. The second spacer **18** is attached to the metalization layer **62** on the second side **26** of the support layer **12** to separate the second plate **22** from the center conductor **14**. Both layers **62** on **24** and **26** are attached to the connection vias **68**.

The first and second plates **20** and **22** may consist entirely of conductive metal such as copper or may consist of a lossy dielectric with copper or silver-plated copper or other suitable metal with low resistivity on each side. These plates form the ground plane **66** disposed over the center conductor **14**. The ground planes **66** of the plates **20** and **22** and the underlying conductive strips **44** and **46** of the center conductor **14** together generate the electromagnetic field in the propagation structure **50**. Variations in spacing of the ground plane **66** from the center conductor **14** may be offset by the line width **64** of the center conductor **14** in order to maintain a substantially constant impedance in the center conductor **14**. Spacing variations may be caused by access openings **65** cut in the ground plane **66** to allow insertion and integration of a device into the suspended transmission line **10**. In this case, the access opening is illustrated covered by a magnetic or other ground cover **67** secured flush with the outside of the plate **20** or **22**.

In the illustrated embodiment, the plates **20** and **22** comprise a conductive material and each form a continuous ground plane **66**. In a particular embodiment, the plates **20** and **22** are copper plates having a thin outer tin layer (not shown) to reduce corrosion and improve solderability. The first plate **20** is attached outwardly of the first spacer **16** to form a first propagation cavity **70** between the first plate **20** and the first conductive strip **44** of the center conductor **14**. The second plate **22** is attached outwardly of the second spacer **18** to form a second propagation cavity **72** between the second plate **22** and the second conductive strip **46** of the center conductor **14**. In this embodiment, the first and second propagation cavities **70** and **72** form the propagation structure **50**.

The propagation cavities **70** and **72** each provide a low-loss medium for propagation of the electromagnetic field generated by a transmitted signal on the center conductor **14**. The low-loss medium is a medium that propagates the electromagnetic field with a dissipation loss on the order of about 0.1 dB/inch or below at microwave frequencies. In the illustrated embodiment, the propagation cavities **70** and **72** are each an air cavity. To prevent moisture from entering the suspended transmission line **10**, the propagation cavities **70** and **72** may include closed cell foam or other suitable low-loss material to displace the air and reduce overall moisture content.

A plurality of mode suppression connectors **68** are formed on either side of the propagation structure **50** to eliminate or reduce interference between the suspended transmission line **10** and nearby or adjacent transmission lines and other devices or circuits in the transmission system. The mode suppression connectors **68** are spaced in accordance with conventional techniques. In one embodiment, the mode suppression connectors **68** are tin plated copper vias extending through the support layer **12** and spacers **16** and **18** between the plates **20** and **22**. The mode suppression connectors **68** are attached to the metalization layers **62** for additional mechanical support and improved mode suppression.

For the suspended transmission line **10**, the geometry, size, and material of the support, spacer, and plate layers **12**, **16**, **18**, **20** and **22** and of the center conductor **14** and propagation cavities **70** and **72** are dependent on the frequency of a signal to be transmitted by the line **10**. The relationship between the transmitted signal frequency and the materials and geometry of the suspended transmission line **10** dictate that the transmission line **10** should be operated below the first cut-off frequency of the potential higher order modes. The onset of the first higher order mode may be approximated by frequency equations for rectangular waveguide and for non-integrated suspended stripline. The mode frequency equation for rectangular waveguide is as follows:

$$f_c = \frac{c0}{2 \cdot a}$$

where:

f_c=TE**10** mode cut-off frequency

cO=the speed of light in a vacuum

a=the enclosure (waveguide) width

The frequency equation for non-integrated suspended striplines is as follows:

$$f_c = \frac{c0}{2 \cdot a}\sqrt{1 - \frac{h}{b}\left[\frac{e_r - 1}{e_r}\right]}$$

where:

f_c=1st higher order mode cut-off frequency

c**0**=the speed of light in vacuum

a=the enclosure width

b=the enclosure height

h=the supporting substrate height

e_r=the relative dielectric constant of the dielectric support layer

These equations provide a close estimation of values for the suspended transmission line **10**, with the non-integrated suspended stripline equation generally providing a closer approximation due to the low cut-off frequency of the suspended transmission line **10**. Other factors have been known to change the cut-off frequency of the suspended transmission line **10**. Such factors include the size and spacing of the mode suppression connectors **68** and the size and spacing of the broadside connectors **48**.

In one embodiment, values obtained for a particular implementation of the suspended transmission line **10** from the equations may be fine tuned using conventional computer simulation techniques and programs, modified to account for the configuration of the suspended transmission line **10**. Suitable programs include ANSOFT EXTRACTOR for 2-D analysis and ANSOFT HFSS (High Frequency Structure Simulator) for 3-D analysis. Further modeling may be done using the BRCTL mode of the HP MDS LINECALC model. The LINECALC model is normally used for a pair of coupled lines as opposed to a single transmission line with mode voltages identical at any cross-section. In the BRCTL model, even mode characteristic impedance is used as twice the characteristic impedance of the suspended transmission line **10** to account for the dual parallel configuration of the center conductor **14**. In addition, because the space between the first and second conductive strips **44** and **46** has nearly the same potential as the first and second conductive strips **44** and **46** when they are held at the same potential by the connectors **48**, the first and second conductive strips **44** and **46** can be regarded as a single thick conductor. Accordingly, the thickness of the conductive strips **44** and **46** must be accounted for in impedance calculations. Other modes of the MDS LINECALC model, finite element analysis, and other suitable techniques are available to simulate and design the suspended transmission line **10**.

In a particular microwave embodiment of the suspended transmission line **10**, the support layer **12** comprises G-10 material having a relative dielectric constant of 4.5 and a thickness of 8 mils. In this particular embodiment, the first and second spacers **16** and **18** each comprise G-10 material and with the adhesion layers **60** having a thickness of 38 mils. The plates **20** and **22** are each copper and have a thickness of 20 mils. Each propagation cavity **70** and **72** has an enclosure width of 240 mils and an enclosure height of 38 mils. The center conductor **14** has an impedance of 50 ohms and comprises silver-plated copper traces **44** and **46** on each side **24** and **26** of the support layer and plated silver connectors **48** extending through the support layer **12** between the silver-plated traces **44** and **46**. The silver-plated traces **44** and **46** each have a thickness of 1.5 mils and a line width of 20 mils. The connectors **48** have a diameter of 13 mils and are each spaced approximately 100 mils apart. The suspended transmission line **10** of this embodiment has a cut off frequency of 14.2 GHz and an upper useful range of about 14 GHz, which provides a margin to account for manufacturing tolerances. Testing of this suspended transmission line **10** showed an insertion loss of 0.02 dB per inch at 1 GHz, an insertion loss is 0.05 dB per inch at 5 GHz, an insertion loss of 0.12 dB per inch at 10 GHz, and an insertion loss of 0.55 dB per inch at 15 GHz.

FIG. **2** illustrates distribution of an electric field **80** in the suspended transmission line **10**. As previously described, the electric field **80** is generated by a propagating electromagnetic signal around the center conductor **14**. This signal may be a microwave, radio, or other suitable frequency signal.

Referring to FIG. **2**, the electric field **80** includes a transverse field **82** generally perpendicular to the conductive strips **44** and **46** and small fringing fields **84** in the support layer **12** at the edges of the conductive strips **44** and **46**. The transverse field **82** comprises the significant part of the electric field **80** and is propagated in the low-loss medium of the propagation cavities **70** and **72**. Accordingly, dissipation or insertion losses are minimal and limited to losses in the fringing field **84**.

FIG. **3** is a flow diagram illustrating a method for fabricating the suspended transmission line **10** of FIG. **1** in accordance with one embodiment of the present invention. In this embodiment, the support, spacer, and ground layers **12**, **16**, **18**, **20**, and **22** are separately fabricated and thereafter laminated together to form the suspended transmission line **10**. It will be understood that the suspended transmission line **10** may be otherwise fabricated and comprise other materials without departing from the scope of the present invention.

Referring to FIG. **3**, the method begins at step **100** in which the conductive traces **44** and **46** are formed on each side **24** and **26** of the support layer **12**. In one embodiment, copper on support layer **12** is patterned and etched to form the conductive traces **44** and **46**. The silver is plated on the resultant copper traces. In this embodiment, the silver plating may be applied outside or at the edges of the cavities **70** and **72** to form the metalization layers **62** and provide an intermediate ground plane on each side **24** and **26** of the support layer **12**. The support layer **12** is cut to size before or after formation of the conductive traces **44** and **46**.

Proceeding to step **102**, connectors **48** are formed in the support layer **12** between the first and second conductive strips **44** and **46**. In one embodiment, the connectors **48** are formed by drilling vias at the intermediate points **40** along the conductive strips **44** and **46** and plating the vias with copper. These vias are then silver plated. As previously described, the connectors **48** provide equal phase and amplitude for a signal between the first and second conductive strips **44** and **46** to reduce electric field coupling. The reduced electric field coupling between conductive strips **44** and **46** lead to reduced insertion loss.

Next, at step **104**, the first and second spacers **16** and **18** are each formed by a pair of opposing strips routed or otherwise formed from a spacer layer. The spacer layer preferably comprises an inexpensive material that is thermally matched to the support layer **12**.

At step **106**, the spacers **16** and **18** are each laminated to opposite sides **24** and **26** of the support layer **12**. The strips for each spacer are positioned along edges of the support layer **12** and displaced from the center conductor **14** to form the propagation cavities **70** and **72**. In one embodiment, the spacers **16** and **18** are laminated to the support layer **12** using a conventional no-flow or low-flow B-stage process. In the B-stage process, partially cured epoxy with glass cloth

reinforcement is attached to the support layer **12** and becomes part of overlying spacer **16** or **18**. The geometry of the glass cloth reinforcement matches that of the overlying spacer **16** or **18** so as to not interfere with the cavity **70** or **72**. The no-flow or low-flow characteristics of the partially cured epoxy prevents or minimizes epoxy flow into the cavities **70** or **72**.

Proceeding to step **108**, the ground plates **20** and **22** are each formed and attached to a spacer **16** or **18**. In one embodiment, each ground plate **20** and **22** is laminated to the respective spacer **16** or **18** using the no-flow or low-flow B-stage process previously described in connection with step **106**. The plates **20** and **22**, in connection with the spacers **16** and **18** and the support layer **12**, form the propagation cavities **70** and **72**.

Next, at step **110**, the laminated layers are pressed together and heated to cure the epoxy and form the basic structure of the suspended transmission line **10**. For the low-flow B-stage process, the layers may be pressed together at a pressure of 250–300 psi and heated at a temperature of 350 degrees Fahrenheit for 90 minutes.

At step **112**, the mode suppression connectors **68** are formed for the suspended transmission line **10**. In one embodiment, the mode suppression connectors **68** are each formed by drilling a via through the plates **20** and **22**, spacers **16** and **18**, and support layer **12**, and plating the vias with copper. In this embodiment, the vias preferably have a diameter greater than 0.04 inches to allow copper and tin plating through the entirety of the vias. In this way, the suspended transmission line **10** is efficiently fabricated further reducing transmission line cost. In addition, conventional multi-layer printed circuit board fabrication techniques may be used in fabrication of the suspended transmission line **10** eliminating the need for the development and testing of new techniques and equipment.

FIG. **4** illustrates a method for transmitting a signal in the suspended transmission line **10**. The method begins at step **114** in which the conductor **114** is supported in the low-loss propagation structure **50**. As previously described, the low-loss propagation structure includes air cavities **70** and **72** formed above and below the conductor **14**.

Proceeding to Step **115**, a signal is transmitted along the conductor **14**. At step **116**, an electric field generated by the signal is substantially contained to the low-loss propagation structure **50**. In addition, at step **118**, a substantially constant phase and amplitude for the signal is maintained in the conductor **14**. Accordingly, line losses are minimized in the suspended transmission line **10**.

In accordance with another aspect of the present invention, a power amplifier or other suitable circuit is embedded into the suspended transmission line **10**. Generally described, the center conductor **14** is configured to accommodate the circuit which is disposed within the propagation structure **50** and coupled to the center conductor **14** to manipulate the transmitted signal. The circuit may manipulate the transmitted signal by dividing or splitting, amplifying, or otherwise altering or modifying the signal. The resulting transmission line structure is self-contained and includes fewer parts than conventional amplifier structures. In addition, the cost of designing, engineering, constructing, and maintaining a separate mechanical housing for the amplifier is substantially eliminated.

FIG. **5** illustrates a suspended transmission line segment **120** having an embedded amplifier **122** in accordance with one embodiment of the present invention. In this embodiment, the suspended transmission line segment **120** and embedded amplifier **122** form a power amplifier structure **124** with radio frequency (RF) input and output ports **126** and **128** that allow connection into existing transmission systems. In one embodiment, connectors allow integration with coaxial cables. Use of the amplifier structure **124** substantially minimizes the design, engineering, construction, and maintenance cost associated with a separate mechanical housing for the amplifier **122**. Further use of the suspended transmission line structure as the transmission line eliminates the need for the RF connectors and further reduces cost while improving performance by minimizing line losses associated with the RF connectors.

Referring to FIG. **5**, the transmission line segment **120** includes a support layer **130**, first and second spacers **132** and **134**, and first and second plates **136** and **138**. In one embodiment, the support, spacer, and plate layers **130**, **132**, **134**, **136**, and **138** are fabricated from materials and configured as previously described in connection with corresponding layers of the suspended transmission line **10**. The various parts of the transmission line segment **120** are laminated together and form a low-loss propagation structure **135** enclosing a conductor **125** supported by the support layer **130**. Mode suppression connectors are formed as also described in connection with the suspended transmission line **10**.

Access openings **137** are formed in the layers **130**, **132**, **134**, **136**, and **138** to accommodate the embedded amplifier **122**. The access openings **137** are covered by covers **139** secured to the outside of the plates **136** and/or **138**.

The conductor **125** for the suspended transmission line segment **120** is an integrated broadside conductor as described in connection with the conductor **14** of the suspended transmission line **10**. The conductor **125** accordingly includes a first conductive trace formed on a first side of the support layer **130**, a second conductive trace formed on a second side of the support layer **130**, and a plurality of connectors that connect the first and second conductive traces at intermediate points along the length of the conductor **125**. As described in more detail below, the conductor **125** is configured to receive the amplifier **122** and extends to the RF ports **126** and **128** at the inlet and the outlet of the power amplifier structure **124**.

The embedded amplifier **122** includes an active device such as a transistor **140**, a power feed structure **142**, and a bias system **144**. In one embodiment, the active device is a MESFET power transistor. As described in more detail below, the bias system **144** is coupled between the power feed structure **142** and the transistor **140** to de-couple power supply voltage from the transmitted signal on the conductor **125**. Accordingly, the transistor bias system **144** also referred to as power supply has substantially no adverse effect on the radio frequency characteristics of the transmitted signal.

The transistor **140** is coupled to the conductor **125** and generates an output signal by amplifying an input signal. The transistor **140** is fitted into the suspended transmission line segment **120** through an access opening **137** in the first plate **136** and is disposed on the support layer **130**. The transistor **140** is secured to the underlying second plate **138** to minimize stress on the support layer **130** and to provide good heat dissipation, thereby minimizing thermal impedance in the conductor **125**. In one embodiment, the first plate **136** and the second plate **138** are fabricated from copper which has improved heat dissipation properties. The transistor **140** may be otherwise suitably disposed and secured within the power amplifier structure **124**.

The transistor **140** is a metal semiconductor field effect transistor (MESFET) or other suitable transistor capable of

amplifying an input signal. The transistor **140** may be internally matched to provide a substantially constant line impedance at its input and output. Alternatively, the conductor **125** can be configured to support a partially matched or a non-matched transistor **140**.

The power feed structure **142** is connected to a power supply (not shown) and provides power to the transistor **140** to amplify the transmitted signal. The power supply is a conventional direct current battery or other suitable power source capable of operating the transistor **140**.

The power feed structure **142** includes voltage nodes **160** and **162** formed on the support layer **130** and feed pins **146** extending through the first plate **136** to the voltage nodes. As described in more detail below, the voltage nodes are coupled to the transistor **140** through the bias structure **144**. The feed pins **146** connect the voltage nodes **160** and **162** to the power supply and are insulated from the first plate **136** by an insulative cover **148** or insulative portions of the cover **148**. In one embodiment, the feed pins **146** consists of two separate pins and are electrically conducted through separate wires that are soldered from the feed pins **146** directly to the voltage nodes **160** and **162**. The two feed pins **146** each provide separate voltages to voltage nodes **160** and **162**. The voltage node **160** carries the necessary gate voltage to the MESFET. The voltage node **162** conducts the necessary drain voltage to the MESFET.

FIG. **6** schematically illustrates the embedded amplifier **122**. Referring to FIG. **6**, the conductor **125** includes an amplifier input section **150** coupled to the input port **126** and an amplifier output section **152** coupled to the output port **128**. The transistor **140** is connected between the amplifier input and output sections **150** and **152** to amplify and transmit the input signal from input port **126** to output port **128**. For the MESFET embodiment, a transistor gate **154** is connected to the amplifier input section **150** and a transistor drain **156** is connected to the amplifier output section **152**. A transistor source **158** is grounded to an intermediate ground plane formed with the conductor **125**. This ground plane is referenced as plate **22** of FIG. **1**.

The power feed structure **142** includes a gate voltage node **160** and a drain voltage node **162**. Power is supplied at each node **160** and **162** by the feed pins **146** (FIG. **4**). The gate voltage node **160** is connected to the transistor gate **154** via a gate power feed line **164** and the amplifier input section **150**. The drain voltage node **162** is connected to the transistor drain **156** via a drain power feed line **166** and the amplifier output section **152**. Accordingly, the conductor **125** is used for both signal and bias power transmission to the transistor. RF blocking capacitors **168** are provided in the conductor **125** on each side of the gate and drain power feed lines **164** and **166** to de-couple power from signal transmission and thereby prevent bias power shorting in the conductor **125** to non-open load impedances. Blocking capacitors **170** also connect each power feed line **164** and **166** to ground in order to de-couple power and signal transmission in the feed line and thereby prevent leakage of the signal frequency from conductor **125** back into the power feed structure **142**. The blocking capacitors **168** and **170** are single or multi-layer ceramic or other suitable capacitor dielectric material.

The bias system **144** includes a quarter wavelength line **172** extending from each power feed line **164** and **166**. The quarter wavelength lines **172** each generate a radio frequency short at a junction **174** with the corresponding power feed line **164** or **166**. The radio frequency short further de-couples the voltage nodes **160** and **162** from the conductor **125** to prevent interference with the transmitted signal. It will be understood that the conductor **125**, transistor **140**, power feed structure **142**, and bias system **144** may be otherwise suitably configured or implemented to amplify the transmitted signal and prevent or minimize amplifier operation from interfering with signal transmission on the conductor **125**.

In a particular embodiment, the power amplifier **122** is a four-watt power amplifier for a 10 GHz transmitted signal. In this embodiment, the transistor **140** is a FUJITSU four-watt FLM0910-4C internally matched MESFET. The conductor **125** has a substantially constant line width of 76 mils. On the gate side of the transistor **140**, the conductor **125** has a length of 400 mils from the input port **126** to the blocking capacitor **168**, a length of **65** mils from the blocking capacitor **168** to a junction **176** with the gate voltage feed line **164**, and a length of 65 mils from the junction **176** to the transistor **140**. On the drain side of the transistor **140**, the conductor **125** has a length of 65 mils from the transistor **140** to a junction **178** with the drain voltage feed **166**, a length of 65 mils from the junction **178** to the blocking capacitor **168**, and a length of 400 mils from the blocking capacitor **168** to the output port **128**. The propagation structure **135** comprises a first air cavity above the conductor **125** and a second air cavity below the conductor **125**. Each air cavity has a width of 240 mils and a height of 87 mils. The gate and drain voltage feed lines **164** and **166** each have a line width of 25 mils and a length of 235 mils from the corresponding junction **176** or **178** with the conductor **125** to the quarter wavelength line **172** and a length of 140 mils from the quarter wavelength line **172** to the corresponding voltage node **160** or **162**. The quarter wavelength lines **172** each have a line width of 80 mils and a length of 268 mils. The blocking capacitors **168** are each 10 pF capacitors. The blocking capacitors **170** are each 100 pF capacitors. The resulting power amplifier may be connected in series with other similar power amplifies to form a two stage power amplifier. In the two stage configuration, the amplifiers have a combined output power of 35.2 dBm with an 11.0 dBm input level, a combined output power of 36 dBm with a 12.5 dBm input level, and a combined output power of 36 dBm at an input level of 14 dBm. Corresponding efficiencies for the capacitor stages are 23.89 percent, 27.5 percent, and 23.3 percent.

FIGS. **7**A–F illustrate the configuration of the support, spacer, and plate layers **130**, **132**, **134**, **136**, and **138** for the 10 GHz, four-watt power amplifier embodiment. In this embodiment, the power amplifier structure **124** has dimensions of 2.75 inches by 2 inches with the ground planes formed on the support layer **130** and by first and second plates **136** and **138** extending 0.025 inches beyond the edges of the remaining layers. The power amplifier structure **124** may be otherwise suitably configured or formed in a segment of a suspended transmission line or in an extended run of a suspended transmission line.

Referring to FIG. **7**A, the first plate **136** includes an access opening **200**, radio frequency connector openings **202**, and mode suppression vias **204**. The mode suppression vias **204** also reduce overall weight in this embodiment. The first plate **136** is a tin-plated copper plate. The access opening **200** is configured to allow insertion of the amplifier and related circuitry into the suspended transmission line segment **120** (also refer to FIG. **5**). A first portion **210** of the access opening **200** allows insertion of the transistor **140**. A second portion **212** of the access opening **200** allows implementation of the bias system **244** while a third portion **214** allows implementation of the power feed structure **142**.

The mode suppression vias **204** are formed and plated as previously described in connection with mode suppression

connectors **68** (FIG. **1**) and comprise a first set of vias **216** each having a diameter of 0.55 inches, in one embodiment, on either side of the propagation structure **135**. A second set of mode suppression vias **218** are formed between the propagation structure **132** and the power feed structure **242** and have a diameter of 0.30 inches in the same embodiment.

Referring to FIG. **7**B, the first spacer layer **132** is formed of G-10 material, in one embodiment, and includes a pathway **220** and mode suppression vias **222**. The pathway **220** includes a first part **224** that is part of a first air cavity of the propagation structure **135**, a second part **226** to allow implementation of the bias system **144**, and a third part **228** to allow implementation of the power feed structure **242**. Air cavities formed by the second and third parts **226** and **228** of the pathway **220** are electrically isolated from the propagation structure **135**. The mode suppression vias **222** are spaced, sized, and formed as previously described in connection with mode suppression vias **204**.

Referring to FIG. **7**C, the support layer **130** is formed of G-10 material, in one embodiment, and includes intermediate ground planes **230**, conductor **125**, bias system **144**, power feed structure **142**, and mode suppression vias **232**. The intermediate ground planes **230**, conductor **125**, bias system **144**, and power feed structure **142** are formed by a single metalization layer on each side of the support layer **130**. Each metalization layer is formed by depositing, patterning, and etching copper and adding silver plate. Preferably, the metalization is mirrored on each side of the support layer **130**. The conductor **125** includes amplifier input section **150** and amplifier output section **152**.

As shown by FIG. **7**C, the conductor **125** includes disparate line widths **134***a* and **134***b* to account for varying heights of the overlying propagation structure **135**. Variance of the conductor **125** line width **134** based on the overhead height of the propagation structure **135** maintains a substantially constant impedance in the conductor **125**. The mode suppression vias **232** are spaced, sized, and formed as previously described in connection with mode suppression vias **204**.

Referring to FIG. **7**D, the second spacer layer **134** is formed of G-10 material and comprises a pathway **240** and mode suppression vias **242**. The pathway **240** includes a first section **244** is part of a second air cavity of the propagation structure **135** and a second section **246** to allow implementation of the bias system **244**. The pathway **240** does not include a section for implementation of the power feed structure **142** as it need only be implemented on one side of the support layer **130**.

Referring to FIG. **7**E, the second plate **138** is formed from tin-plated copper and includes an access opening **250**, radio frequency connector openings **252**, and mode suppression vias **254**. The access opening **250** is configured to secure the transistor **140** to the second plate **138**. As previously described, this minimizes stress on the support layer **130** and provides good heat dissipation characteristics for the transistor **140** during operation of the power amplifier structure **124**. The radio frequency connector openings **252** and mode suppression vias **254** are configured and formed as previously described in connection with corresponding structures of the first plate **136**. After formation of each layer **130**, **132**, **134**, **136**, and **138**, the layers are laminated together to form the suspended transmission line segment **120** (refer to FIG. **5**).

Referring to FIG. **7**F, after formation of the suspended transmission line segment **120**, the mode suppression vias **204**, **222**, **232**, **242**, and **254** are drilled and plated to form mode suppression connectors. A through opening **260** is formed in each of the layers **130**, **132**, **134**, and **136**. The transistor **140**, feed pins **146**, and capacitors **168** and **170** are embedded into the transmission line segment **120** by inserting the devices through the openings and soldering or otherwise securing the devices to the conductor **125**, power feed structure **142**, and bias system **144**. Covers **139** are soldered or otherwise secured over the openings. Accordingly, the transmission line structure is self-contained and ultimately lower cost than standard industry implementations.

FIG. **8** illustrates a method for amplifying a signal in the power amplifier structure **124**. The method begins at step **280** to support the conductor **125** in the low-loss propagation structure **135** of the suspended transmission line segment **120**. Next, at step **282**, a signal is transmitted along the conductor **125**.

Proceeding to step **284**, the signal is amplified within the low-loss propagation structure **135**. As previously described, the signal is amplified by the transistor **140** which is connected to amplifier input and output sections **150** and **152** of the conductor **125**.

Next, at step **286**, an electric field generated by the signal is substantially contained to the low-loss propagation structure **135**. In addition, at step **286**, a substantially constant phase and amplitude for the signal is maintained in the conductor **125**. Accordingly, line losses are minimized in the suspended line segment **120**. Step **286** leads to the end of the process by which the signal is amplified in a low cost suspended transmission line with low line loss.

Although the present invention has been described with several embodiments, various changes and modifications may be suggested to one skilled in the art. It is intended that the present invention encompass such changes and modifications as fall within the scope of the appended claims.

What is claimed is:

1. A suspended transmission line with an embedded amplifier, comprising:

a support layer;

a conductor supported on the support layer between first and second plates each plate having a ground plane, the conductor comprises a first conductive strip supported on a first side of the support layer, a second conductive strip supported on a second side of the support layer, an amplifier input section and an amplifier output section;

a propagation structure between the first and second plates to substantially contain an electric field generated by a signal transmitted on the conductor; and

an amplifier coupled to the amplifier input and output sections of the conductor and at least substantially disposed between the first and second plates, the amplifier operable to amplify an input signal received on the amplifier input section to generate an output signal for transmission on the amplifier output section.

2. The suspended transmission line of claim **1**, wherein the amplifier comprises:

a transistor coupled between the amplifier input and output sections of the conductor and disposed within the propagation structure; and

a power feed structure operable to supply power to the transistor, the power feed structure coupled to the amplifier input and output sections of the conductor.

3. The suspended transmission line of claim **2**, further comprising a bias system coupling the power feed structure to the amplifier input and output sections of the conductor.

4. The suspended transmission line of claim **3**, the bias system comprising:

a first power lead connecting the power feed structure to the amplifier input section of the conductor;

a first quarter wavelength line extending from the first power lead and operable to form a radio frequency short in the first power lead;

a second power lead connecting the power feed structure to the amplifier output section of the conductor; and a second quarter wavelength line extending from the second power lead and operable to form a radio frequency short in the second power lead.

5. The suspended transmission line of claim **1**, further comprising the propagation structure at least substantially enclosing the amplifier.

6. The suspended transmission line of claim **1**, further comprising the propagation structure entirely enclosing the amplifier.

7. The suspended transmission line of claim **1**, wherein the support layer comprises a lossy material.

8. The suspended transmission line of claim **7**, wherein the lossy support layer comprises an epoxy glass material.

9. The suspended transmission line of claim **1**, wherein the first and second conductive strips substantially mirror each other.

10. The suspended transmission line of claim **1**, wherein the conductor further comprises a plurality of connectors extending between the first and second conductive strips at intermediate points along the length of the conductor.

11. The suspended transmission line of claim **10**, wherein the connectors are substantially evenly spaced along the length of the conductor.

12. The suspended transmission line of claim **1**, wherein the support layer, conductor, and propagation structure have a configuration and size to transmit a radio frequency signal.

13. The suspended transmission line of claim **1**, wherein the propagation structure comprises a first air cavity between the conductor and the first plate and a second air cavity between the conductor and the second plate.

14. The suspended transmission line of claim **13**, further comprising:

a first spacer between the support layer and the first plate to form the first air cavity over the conductor; and

a second spacer between the support layer and the second plate to form the second air cavity over the conductor.

15. The suspended transmission line of claim **14**, further comprising a plurality of mode suppression connectors connecting the first and second plates at spaced intervals.

16. A suspended transmission line with an embedded amplifier, comprising:

a support layer;

a conductor supported on the support layer between first and second plates each plate having a ground plane, the conductor including an amplifier input section and an amplifier output section;

a propagation structure between the first and second plates to substantially contain an electric field generated by a signal transmitted on the conductor, the propagation structure comprising a first air cavity between the conductor and the first plate and a second air cavity between the conductor and the second plate;

a first spacer between the support layer and the first plate to form the first air cavity over the conductor;

a second spacer between the support layer and the second plate to form the second air cavity over the conductor;

a plurality of mode suppression connectors between the first and second plates at spaced intervals; and

an amplifier coupled to the amplifier input and output sections of the conductor and at least substantially disposed between the first and second plates, the amplifier operable to amplify an input signal received on the amplifier input section to generate an output signal for transmission on the amplifier output section.

17. The suspended transmission line of claim **16**, further comprising:

the first cavity having disparity in height over the conductor; and

the conductor comprising disparity in line width to maintain a substantially constant impedance in the conductor.

18. A suspended transmission line with an embedded circuit, comprising:

a support layer;

a conductor supported on the support layer between first and second plates each plate having a ground plane, the conductor comprises a first conductive strip supported on a first side of the support layer, a second conductive strip supported on a second side of the support layer, a circuit input section and a circuit output section;

a propagation structure between the first and second plates to substantially contain an electric field generated by a signal transmitted on the conductor;

an active circuit coupled to the circuit input and output sections of the conductor and at least substantially disposed between the first and second plates, the circuit operable to manipulate an input signal received on the circuit input section to generate an output signal for transmission on the circuit output section; and

a power feed structure operable to supply power to the circuit, the power feed structure coupled to the circuit input and output sections of the conductor.

19. The suspended transmission line of claim **18**, wherein the propagation structure at least substantially encloses the circuit.

20. The suspended transmission line of claim **18**, wherein the propagation structure entirely encloses the circuit.

21. A method for transmitting a radio frequency signal in a transmission line, comprising:

supporting a first conductive strip on a first side of a support layer in a low-loss propagation structure between opposing ground planes;

supporting a second conductive strip on a second side of the support layer;

connecting the first and second conductive strips at spaced intervals along the length of the conductors to maintain a substantially constant phase and amplitude for the radio frequency signal;

transmitting the signal along the first and second conductive strips;

amplifying within the low-loss propagation structure the signal as transmitted on the first and second conductive strips; and

containing an electric field generated by the signal substantially to the low-loss propagation structure.

22. The method of claim **21**, further comprising supporting the first and second conductive strips on a lossy support layer.

23. The method of claim **21**, further comprising:

supplying power on the conductor to amplify the signal; and

de-coupling the power from the radio frequency performance of the conductor.

24. A suspended transmission line with an embedded circuit, comprising:

a lossy material support layer;

a conductor supported on the support layer between first and second plates each plate having a ground plane, the conductor comprises a first conductive strip supported on a first side of the support layer, a second conductive strip supported on a second side of the support layer, a circuit input section and a circuit output section;

a propagation structure between the first and second plates to substantially contain an electric field generated by a signal transmitted on the conductor; and

a circuit coupled to the circuit input and output sections of the conductor and at least substantially disposed between the first and second plates, the circuit operable to manipulate an input signal received on the circuit input section to generate an output signal for transmission on the circuit output section.

25. The suspended transmission line of claim 24, wherein the conductor further comprises a plurality of connectors extending between the first and second conductive strips at intermediate points along the length of the conductor.

26. A suspended transmission line with an embedded circuit, comprising:

a support layer;

a conductor supported on the support layer between first and second plates each plate having a ground plane, the conductor comprising a first conductive strip supported on a first side of the support layer and a second conductive strip supported on a second side of the support layer, the conductor including a circuit input section and a circuit output section;

a propagation structure between the first and second plates to substantially contain an electric field generated by a signal transmitted on the conductor; and

a circuit coupled to the circuit input and output sections of the conductor and at least substantially disposed between the first and second plates, the circuit operable to manipulate an input signal received on the circuit input section to generate an output signal for transmission on the circuit output section.

27. The suspended transmission line of claim 26, wherein the conductor further comprises a plurality of connectors extending between the first and second conductive strips at intermediate points along the length of the conductor.

28. A suspended transmission line with an embedded amplifier, comprising:

a support layer;

a conductor supported on the support layer between first and second plates each plate having a ground plane, the conductor including an amplifier input section and an amplifier output section;

a propagation structure between the first and second plates to substantially contain an electric field generated by a signal transmitted on the conductor;

an amplifier coupled to the amplifier input and output section of the conductor and at least substantially disposed between the first and second plates, the amplifier operable to amplify an input signal received on the amplifier input section to generate an output signal for transmission on the amplifier output section;

a power feed structure operable to supply power to the amplifier, the power feed structure coupled to the amplifier input and output sections of the conductor;

a first power lead connecting the power feed structure to the amplifier input section of the conductor;

a first quarter wave-length line extending from the first power lead and operable to form a radio frequency short in the first power lead;

a second power lead connecting the power feed structure to the amplifier output section of the conductor; and

a second quarter wave-length line extending from the second power lead and operable to form a radio frequency short in the second power lead.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,518,844 B1
DATED : February 11, 2003
INVENTOR(S) : James R. Sherman et al.

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

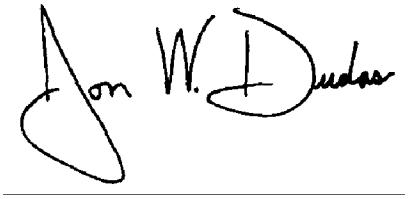
Title page,
Item [56], **References Cited**, FOREIGN PATENT DOCUMENTS, delete "H01P/6/08" and insert -- H01P/6/06 --.

Column 5,
Line 43, delete "pacer" and insert -- spacer --.

Column 6,
Line 64, after "c" delete "O" and insert -- 0 --.

Signed and Sealed this

Twenty-third Day of March, 2004



JON W. DUDAS
Acting Director of the United States Patent and Trademark Office