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(71) **Applicant** *(for all designated States except US):* **ARIZONA BOARD OF REGENTS AND ON BEHALF OF ARIZONA STATE UNIVERSITY** [US/US]; The Brickyard, 699 S. Mill Avenue Suite 601, Room 691 AA, Tempe, AZ 85281 (US).

(72) **Inventor; and**
(75) **Inventor/Applicant** *(for US only):* **ABBASPOUR-TAMIJANI, Abbas** [IR/US]; 10414 E Star Of The Desert Dr., Scottsdale, AZ 85255 (US).

(74) **Agent: MIN, Eric;** Fulbright & Jaworski L.l.p., 600 Congress Ave., Suite 2400, Austin, TX 78701 (US).

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(54) **Title:** HYBRID INTEGRATED MEMS RECONFIGURABLE ANTENNA ARRAY (HIMRA)

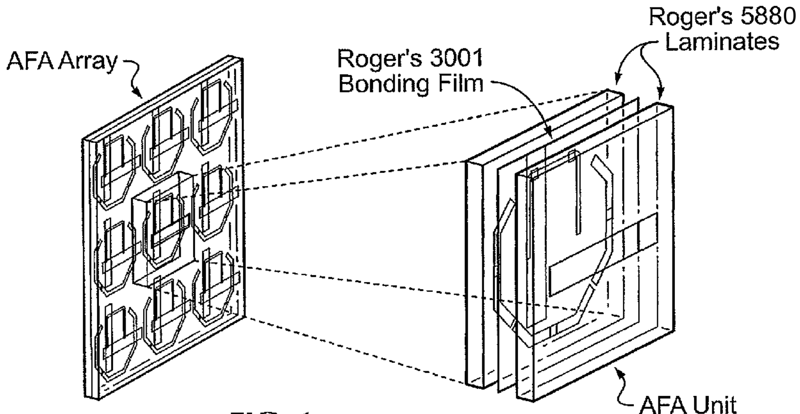

FIG. 1

(57) **Abstract:** A phased array antenna is disclosed that uses hybrid integration of the wave coupled MEMS phase shifters and a substrate integrated slotted waveguide antenna array and associated feed network. The antenna includes a substrate integrated waveguide (SIW) slot array; an adapter inner layer having an upper surface facing the SIW array, the adapter inner layer having a plurality of cavities formed therethrough; a plurality of MEMS chips positioned within the cavities; and a SIW feed network facing a lower surface of the SIW slot array. The adapter inner layer may include upper and lower low-frequency substrate layers stacked with an intervening bonding film. One of the low-frequency substrate layers may further include bias lines etched on a surface thereof.

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DESCRIPTION

HYBRID INTEGRATED MEMS RECONFIGURABLE ANTENNA ARRAY (HIMRA)

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. Provisional Patent Application Ser. No. 60/955,271, filed August 10, 2007, which is incorporated by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made in part with United States government support under Grant No. ECS-0524805 awarded by the National Science Foundation. The United States government has certain rights in the invention.

BACKGROUND

The present invention relates generally to radio systems and, more particularly, to systems and methods for Electronically Scanned Antennas (ESA) in the millimeter-wave frequencies (30-100 GHz).

Electronically Scanned Antennas (ESA) are an integral part of modern radar systems. Future communication system will also heavily depend on the beam forming capability of the antenna for an efficient utilization of the electromagnetic spectrum and RF power. Applications include surveillance radars, electronic warfare, WLAN hubs and cellular communication base stations, ad-hoc wireless network nodes, reconfigurable and multi-band satellite antennas, beam-locked satellite receivers for in-motion platforms, and collision-avoidance radars. Examples of such devices can be found in U.S. Patent Nos. 6,184,827 of Dendy et al, 6,396,449 of Osterhues et al., 6,653,985 of Sikina et al. and 7,151,507 of Herring (among others), each of which is incorporated by reference herein in its entirety.

Certain difficulties associated with the implementation of ESA's at millimeter-wave frequencies can be attributed to a number of factors, including the loss of the feed network, poor performance of the (semiconductor) phase shifters, misalignments and other assembly imperfections, and complexity and radiation effects of the bias circuitry. RF MEMS switches with electrostatic actuation present low loss, high linearity, and extremely small power consumption (see, e.g., G. M. Rebeiz and J. B. Muldavin, "RF MEMS switches and switch circuits," IEEE Microwave Magazine, vol. 2, pp. 59-71, Dec. 2001, which is incorporated by reference herein in its entirety), and are good alternatives to GaAs-based devices. However, in the standard approach, such MEMS switches need to be individually packaged and interfaced with the rest of the circuit through RF signal pads. This requirement increases the assembly cost and is amenable to the adverse parasitic effects of the package and RF interconnects. Also, this approach generally requires the implementation of the feed network in microstrip or similar planar technologies which can be very inefficient in large millimeter-wave arrays.

Quasi-optical array concepts in the form of reflect-arrays (RA) and lens-arrays (LA) are extensively used for beam forming in the millimeter-wave frequencies, mainly since they dispense with the lossy feed network to use free space as the feeding and power combining medium. Also wafer scale integration and batch packaging of the MEMS devices within the structure of the RA's and LA's can overcome many of the difficulties associated with phase arrays. However, wafer scale integration can also be costly and limiting in the case of large arrays, and requires a high degree of control over the fabrication process that may prove impractical or low-yield. In addition, space-fed are inevitably three-dimensional and can suffer from adverse effects such as spill-over loss, aperture taper loss, and feed blockage.

SUMMARY

The present invention includes embodiments of an array architecture based on the hybrid integration of the wave coupled MEMS phase shifters and a substrate integrated slotted waveguide antenna array and associated feed network. Embodiments of the present methods can form a basis for fabrication of inexpensive, low-loss, light-weight, and thin millimeter-wave ESA structures. Such embodiments provide a low-cost, low-profile, and efficient integrative implementation of ESAs in the millimeter-wave frequencies. Some embodiments may be based on a hybrid integration of a class of wave-coupled self-packaged RF MEMS phase shifting devices within the structure of an adapter inner layer which may be placed between a waveguide feed network and a slotted waveguide antenna array and may be fabricated in a printed circuit board (PCB) process. The feed network and antenna array can be

implemented using substrated integrated waveguide technology to enable fabrication in a PCB process. The present devices and methods significantly reduce the form factor, weight, and fabrication costs and dramatically improve the RF performance over prior phased array methods. Some embodiments include an array architecture based on the hybrid integration of the wave coupled MEMS phase shifters and a microstrip antenna array and associated feed network. Some embodiments of the present methods form a basis for inexpensive, low-loss, light-weight, and thin millimeter-wave ESA structures.

According to one aspect of the invention, a phased array antenna may include a substrate integrated waveguide (SIW) slot array; a adapter inner layer having an upper surface facing the SIW array, the adapter inner layer having a plurality of cavities formed therethrough; a plurality of MEMS chips positioned within the cavities; and a SIW feed network facing a lower surface of the SIW slot array.

According to a feature of the invention, the adapter inner layer may include upper and lower low-frequency substrate layers stacked with an intervening bonding film. One of the low-frequency substrate layers may further include bias lines etched on a surface thereof.

According to another feature of the invention, the MEMS chips may be constructed using a double stack of low loss RF substrates and embedded in the cavities created in the adapter inner layer. The MEMS chips may be bonded to bias pads using, for example, conductive epoxy or solder. Each of the MEMS chips may include a (i) base substrate accommodating a slot antenna on its bottom surface and a plurality of stripline resonators and MEMS switches on the top; and (ii) a cap substrate accommodating switch cavities on the bottom and a slot antenna on the top surface. The base and cap substrates may be made of low loss RF materials such as, for example, pyrex glass, quartz, sapphire, Alumina, or high-resistivity silicon.

According to another feature of the invention, the SIW feed network may include a double-clad microwave laminate, a waveguide structure formed by the metal cladding and a plurality of closely spaced metallized via-holes, and a plurality of coupling slots etched in the metal clad on one side of the waveguide branches.

According to another feature of the invention, the SIW slot array may include a double-clad microwave laminate, a parallel waveguide structure formed by the top and bottom metal claddings and a plurality of closely-spaced metallized via holes. The radiating elements may be slot antennas etched on the top cladding. A plurality of coupling slots etched on the bottom cladding may be used to couple the antenna array to MEMS phase-shifting elements embedded within the adapter inner layer.

According to another aspect of the invention, a method of manufacturing for a phased array antenna may include steps of loading an array of MEMS chips within an adapter inner layer; and bonding together a substrate integrated waveguide (SIW) slot array, the MEMS loaded adapter inner layer, and a slot array board.

According to a feature of the invention, the method may further include a method of manufacturing the MEMS chips including steps of fabricating a base wafer and fabricating a cap wafer. Fabrication of the base wafer may include steps of depositing a metallic film onto the back side of a dielectric substrate and patterning the slot antennas into this metal layer; depositing and patterning high resistivity bias lines on a top side of the substrate; forming the first isolating layer on the bias lines; depositing the first conductive film on the first insulating layer; patterning the first metallic film to form the seed layer for stripline resonators; forming the second isolating layer on top of the seed layer for the capacitive switches; depositing and patterning the sacrificial layer for the switches and air bridge structures; depositing and selectively electroplating the second metallic film on the second insulating layer; etching the second metallic film to form resonators and switches; and releasing the switches by removing the sacrificial layer. Fabrication of the cap wafer may include steps of depositing, patterning and electroplating to form slot antennas on a top side of a substrate, and etching switch cavities on a bottom side of the substrate.

It should be noted that, as used herein:

The term "coupled" is defined as electromagnetically connected, although not necessarily through wires or metallic traces, and not necessarily directly connected.

The terms "a" and "an" are defined as one or more unless this disclosure explicitly requires otherwise.

The term "substantially," "about," and their variations are defined as being largely but not necessarily wholly what is specified as understood by one of ordinary skill in the art, and in one non-limiting embodiment, the substantially refers to ranges within 10%, preferably within 5%, more preferably within 1%, and most preferably within 0.5% of what is specified.

The terms "comprise" (and any form of comprise, such as "comprises" and "comprising"), "have" (and any form of have, such as "has" and "having"), "include" (and any form of include, such as "includes" and "including") and "contain" (and any form of contain, such as "contains" and "containing") are open-ended linking verbs. As a result, a method or device that "comprises," "has," "includes" or "contains" one or more steps or elements possesses those one or more steps or elements, but is not limited to possessing only those one or more elements. Likewise, a step of a method or an element of a device that "comprises," "has," "includes" or "contains" one or more features possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a device or structure that is configured in a certain way is configured in at least that way, but may also be configured in ways that are not listed.

The following abbreviations, acronyms and terms of art are used throughout the present disclosure:

AFA	Antenna-Filter-Antenna
CPD	Critical Point Dryer
ESA	Electronically Scanned Antennas
FR4	An Epoxy Laminate Material
HIMRA	Hybrid Integrated MEMS Reconfigurable Array
LA	Lens-Arrays
MEMS	Micro Electro-Mechanical Systems
MMRAA	Monolithic MEMS Reconfigurable Aperture Antenna
PMMA	Polymethyl Methacrylate (PMMA) or Poly (Methyl 2-Methylpropenoate)
RA	Reflect-Arrays
RF	Radio Frequency
RIE	Reactive Ion Etching
SIW	Substrate Integrated Waveguide
SU8	A Negative, Epoxy-Type, Near-UV Photoresist
WLAN	Wireless Local Area Network

Other features and associated advantages will become apparent with reference to the following detailed description of specific embodiments in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The following drawings form part of the present specification and are included to further demonstrate certain aspects of the present invention. The invention may be better understood by reference to one or more of these drawings in combination with the detailed description of specific embodiments presented herein.

FIG. 1 is a diagram of a reconfigurable AFA array with a three-layer structure;

FIG. 2A is a diagram of a resonator configuration operating to provide 0 degrees of phase shift;

FIG. 2B is a diagram of a resonator configuration operating to provide 180 degrees of phase shift;

FIG. 2C is a diagram of a resonator configuration operating to provide 90 degrees of phase shift;

FIG. 2D is a diagram of a resonator configuration operating to provide 270 degrees of phase shift;

FIG. 3 is a simulated amplitude of the frequency response of an embodiment of a two-bit AFA in its four modes of operation;

FIG. 4 is a simulated phase of the frequency response of an embodiment of a two-bit AFA in its four modes of operation;

FIG. 5 is a diagram of the fabrication and assembly of a MEMS AFA device according to an embodiment of the invention;

FIG. 6 depicts top and bottom views of an embodiment of a substrate integrated waveguide feed network;

FIG. 7 depicts top and bottom views of an embodiment of a substrate integrated waveguide (SIW) slot array;

FIG. 8A depicts the fabrication and assembly of the adapter inner layer in an embodiment of a Multi-layer integration of a Hybrid Integrated MEM Reconfigurable Array (HIRMA);

FIG. 8B depicts the assembly of the MEMS dies in the adapter inner layer for an embodiment of a Multi-layer integration of a HIRMA; and

FIG. 8C depicts vertical stacking of the SIW feed network, MEMS loaded adapter inner layer, and the SIW slot array to construct an embodiment of of a HIRMA.

FIG. 9 depicts an embodiment of the present methods for assembling a phased array antenna.

FIG. 10 depicts an embodiment of the present methods for delivering and extracting a radio frequency signal to and from a MEMS phase-shifter chip.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The invention and the various features and advantageous details are explained more fully with reference to the nonlimiting embodiments that are illustrated in the accompanying drawings and detailed in the following description. Descriptions of well known starting materials, processing techniques, components, and equipment are omitted so as not to unnecessarily obscure the invention in detail. It should be understood, however, that the detailed description and the specific examples, while indicating embodiments of the invention, are given by way of illustration only and not by way of limitation. Various substitutions, modifications, additions, and/or rearrangements within the spirit and/or scope of the underlying inventive concept will become apparent to those skilled in the art from this disclosure.

Prior devices have included a fully-integrated self-packaged Monolithic MEMS Reconfigurable Aperture Antenna (MMRAA) in the form of a lens-array. This lens-array may be constructed as an array of reconfigurable antenna-filter-antenna (AFA) elements, as depicted in FIG. 1. Each AFA may be a three-layer metallic structure, comprised of receive and transmit antennas, and an interconnecting resonant circuit, and operate as a bandpass filter with radiative ports. Fixed AFA elements can be used in designing bandpass frequency selective-surfaces (FSS) and fixed lens-array structures. Further details of such a device can be found in publications such as A. Abbaspour-Tamijani, K. Sarabandi, G. M. Rebeiz, "Antenna-filter-antenna arrays as a class of bandpass frequency selective surfaces," IEEE Trans. Microwave Theory and Techniques, vol. 52, pp. 1781-1789, Aug. 2004 and A. Abbaspour-Tamijani, K. Sarabandi, G.M. Rebeiz, "A millimeter-wave bandpass filter-lens array," IET Proceeding: Microwaves, Antennas & Propagation, Volume 1, Issue 2, April 2007 Page(s):388 - 395, both articles being incorporated by reference in their entireties. Integrating MEMS switches within the AFA structure allows a reconfigurable filtering response, which can be used to adaptively control the transfer characteristics of the unit cell. Using this technique, multi-mode AFA elements can be designed (as shown in FIGs. 2A-2D) with a bandpass response and 2-bit phase shift function as shown in FIGs. 3-4.

MEMS-enabled AFA elements can be used as the building blocks of wide-scan ESAs as described in CC. Cheng, A. Abbaspour-Tamijani, "Study of two-bit reconfigurable antenna-filter-antenna elements for adaptive millimeter-wave lens-arrays," IEEE Transactions on Microwave Theory and Techniques, 54, pp 4498-4506, Dec. 2006, incorporated by reference herein in its entirety.

While the lens-based MMRAA concept eliminates the loss of the feed network and can be used to generate a fully reconfigurable radiation pattern, the depth of the complete system including the lens-array and the feed antenna can be undesirable in many applications. Also the spill-over losses can drastically reduce the efficiency of the lens-based design. To remedy these problems, embodiments of the present invention incorporate an array concept based on the combination of reconfigurable AFA elements and a low-loss constrained feed network composed of substrate integrated waveguides (SIW). (See, for example, F. Xu and K. Wu, "Guided-wave and leakage characteristics of substrate integrated waveguide," IEEE Trans. Microwave Theory and Techniques, vol. 53, pp. 66-73, Jan. 2005 and S. Yang, S.H. Suleiman, A.E. Fathy, "Ku-band slot array antenna for low profile mobile DBS applications: printed vs. machined," 2006 IEEE International Antennas and Propagation Symposium, Digest of papers, pp 3137-3140, each of which is incorporated herein in its entirety.) In the present approach, the AFA elements may be fabricated separately and integrated with the RF antenna structure in a self aligned multi-layer PCB process. The hybrid integration method offers a cost effective method for production scale fabrication of planar ESA's.

The concept of Hybrid Integrated MEMS Reconfigurable Antenna Array (HIMRA) is further detailed herein. The following example is included to demonstrate a particular embodiment of the invention. It should be appreciated by those of skill in the art that the techniques disclosed in this example represent techniques found to function well in the practice of the invention. However, those of skill in the art should, in light of the present disclosure, appreciate that many changes can be made in the specific embodiments which are disclosed and still obtain a like or similar result without departing from the spirit and scope of the invention.

Although HIMRA can be used for designing general reconfigurable antennas, for purposes of the present example and ease of illustration, the following description is limited to a case of an array with beam-forming capability only in the E-plane. Those skilled in the art will recognize that the invention is equally applicable to other configurations not limited to beam forming only in the E-plane.

Hybrid Integrated MEMS Reconfigurable Array

HIMRA presents a planar low-cost platform for the implementation of MEMS based phased array antennas. HIMRA combines MEMS fabrication technology with a simple PCB process to form multilayer, seamless, self-packaged, self-aligned antenna array structures suitable for production scale fabrication (see FIGs. 8A - 8C). While the use of MEMS switch technology allows for high RF performance phase shifters, a commercial multi-layer PCB fabrication provides an inexpensive basis for the fabrication of the low-loss RF feed network, antenna array, and the bias circuitry, in a fashion that can be readily applied to both small and large arrays. In the present embodiments, MEMS phase-shifters are realized as reconfigurable AFA devices that may be fabricated in the form of self-packaged units and embedded within the PCB structure through a layer of perforated laminate board known as an interposer, or "adapter inner layer."

The concept and function of the adapter inner layer in HIMRA is similar to that of the silicon interposer in a Self-Aligned Wafer-Level Integration Technology (SAWLIT) (see, e.g., H. Sharifi, T.Y. Choi, S. Mohammadi, "Self-aligned wafer-level integration technology with high-density interconnects and embedded passives," IEEE Trans. Devices and Packaging, vol. 30, pp. 11-18, Feb. 2007, each of which is incorporated by reference herein in its entirety), acting as a platform for the integration of various semiconductor and MEMS chips with the RF substrate containing the antenna and integrated passives. However, unlike SAWLIT, HIMRA takes advantage of electromagnetic coupling to achieve a seamless transition between the MEMS chip, the feed network and the antenna array. A description of the structure and fabrication of embodiments of HIMRA and embodiments of the individual components of HIMRA follows.

Reconfigurable AFA Elements

MEMS phase shifters in general can be implemented using a variety of methods, and can be generally divided into two groups: a) devices with continuously varying phase shift, and b) devices with quantized phase shift. The latter group are often referred to as multi-bit or digital phase shifters. Common methods for implementing continuously varying phase shifters rely on MEMS varactors. Well known examples include distributed MEMS transmission line and lumped element variable delay line filters. Digital phase shifters are commonly implemented using MEMS switches, in the form of switchable length transmission lines or reflective phase shifters with variable length loading stubs.

Implementation of digital phase-shifters in the form of reconfigurable Antenna-Filter-Antenna (AFA) elements has been described in prior publications coauthored by the inventor (see, e.g., CC. Cheng, A. Abbaspour-Tamijani, "Study of two-bit reconfigurable antenna-filter-antenna elements for adaptive millimeter-wave lens-arrays," IEEE Transactions on Microwave Theory and Techniques, 54, pp 4498-4506, Dec. 2006 and CC. Cheng, A. Abbaspour-Tamijani, Craig Birtcher, "Millimeter-wave beam-steering using an array of reconfigurable antenna-filter-antenna elements," 2006 International Microwave Symposium, San Francisco, CA, Digest of papers, pp. 449-452, each of which is incorporated herein in its entirety). In this implementation, the delivery of the input signal and extraction of the output signal are achieved electromagnetically and through input/output slot antennas. A derivation of this concept that can be used in HIMRA will be presented in this section.

Regardless of the method of implementation, any MEMS phase shifter chip can lend itself to the HIMRA integration process as long as certain provisions are made to ensure a suitable physical interface (such as a stepped wall package structure) and electromagnetic input/output coupling. These requirements will be detailed in the following paragraphs for the case of reconfigurable AFA.

The reconfigurable AFA devices of some embodiments of the present disclosure are similar to the type initially developed for MMRAA (see, e.g., C C Cheng, A. Abbaspour-Tamijani, "Study of two-bit reconfigurable antenna-filter-antenna elements for adaptive millimeter-wave lens-arrays," IEEE Transactions on Microwave Theory and Techniques, 54, pp 4498-4506, Dec. 2006). The embodiment depicted in FIGs. 1 and 2A - 2D, comprises two resonant slot antennas and a switchable stripline resonant circuit. Five MEMS switches are used to configure the stripline circuit in one of four modes of operation. Together with the antennas, the stripline resonators can form a 3- or 4-pole filter with four distinct possible values of mid-band phase delay as presented in FIGs. 3 and 4. The multi-valued phase delay allows embodiments of the AFA device to function as a two-bit phase-shifter.

When intended for use in space-fed arrays such as MMRAA, AFAs may be designed to produce the required transmission response between incident and transmitted plane waves while operating in a (quasi) periodic array environment. In some embodiments of HIMRA, individual AFA devices are placed between two perpendicularly oriented SIW waveguides with the slot antennas coupling to the incident wave and transmitted waves in these waveguides. The frequency response, hence, depends on the waveguide dimensions and orientation of the slots relative to the waveguides, and the AFA elements may be designed and optimized with for a given waveguide geometry.

An embodiment of an AFA structure (MEMS phase-shifter chips **350)** may be fabricated using two pieces of glass or quartz substrates, herein referred to as base and cap wafers (FIG 5). The fabrication of the base wafer **351** may include depositing 500A/5000A Ti/AU and patterning the slot antennas **500** on the back side using a standard liftoff process. On the top side, the first of the SiCr bias lines **358** may be deposited and patterned, followed by an isolating layer of PECVD SiN. A 500A/5000A Ti/Au film may then be deposited and patterned using liftoff to form the seed layer for the stripline resonators **357.** The protective dielectπc layer for the capacitive MEMS switches **356** may then be formed using a second film of SiN. A PMMA sacrificial layer may then be spun and patterned using RIE, which may also used for defining the dimples. Another 500A/5000A Ti/Au may then be blanket sputtered, and selectively electroplated with 3-4 μm Au to decrease the Ohmic loss in both resonators and slot antennas. Finally, resonators and switches may be defined by etching and the cantilevers may be released in a CPD (e.g., carbon dioxide (CO_2) dry release using critical point drying).

The fabπcation of the cap wafer **352** of some embodiments may include deposition, patterning and electroplating of the slot antennas on the top side, and etch definition of 10 μm deep switch cavities **355** on the bottom side. Bonding of the cap and base wafers in the laboratory environment can be performed by using SU8 (a negative, epoxy-type, near-UV photoresist based on EPON SU-8 epoxy resin) or other suitable photoresist and applying heat. Other bonding scenarios such as eutectic bonding or glass frit may be used for the production scale fabrication of some embodiments. The bias pads **353** for the MEMS switches may be exposed through a cascade configuration for stacking the cap and base wafers (FIG. 5). To achieve this configuration, the boundaries of the cap die may be cut half-way (half cut cavity **354)** through the thickness on the bottom side of the cap wafer using a dicing saw before bonding the two wafers The dicing may be completed after the wafers are bonded together.

In the described embodiment of the AFA structure each switch may be enclosed inside a dedicated cavity in the cap wafer. Furthermore, the RF signal may be coupled in and out of the AFA electromagnetically using the slot antennas which eliminates the need for any RF connections. The embodiment of the AFA element, hence, can be considered as a self-packaged device, where the electromagnetic structure provides an enclosure for the MEMS switches.

SIW Feed Network

It is possible to implement the feed network for HIMRA using any planar technology, for example microstrip. However, planar transmission lines may suffer from excessive attenuation at millimeter-wave frequencies and therefore prove to be poor candidates for implementing the feed network, particularly in large arrays. An alternative approach used in embodiments of the present disclosure is based on SIW technology that can dramatically improve the efficiency and is simply manufacturable using a PCB process. Similar to conventional waveguide feeds, the SIW feed for a one dimensional ESA can be implemented as a single slotted waveguide section operating in traveling- or standing-wave modes. Referring to FIG. 6, feed layer **200** may include, for example, coupling slots **500,** E-plane feed network 210, and CPW input port **211.**

SIW Slotted Waveguide Array

To further improve the efficiency of embodiments of the present disclosure, the radiating elements of the array can also be implemented as waveguide fed slot antennas. Slotted waveguides have been traditionally used for the low-loss implementation of fixed beam antenna arrays (see, e.g., R. Elliott, W. O'Loughlin, "The design of slot arrays including internal mutual coupling," IEEE Trans. Antennas and Propagation, vol. 34, pp. 1149-1 154, Sept. 1986; A.G, Derneryd, S.R Rengarajan, S.-O Brattstrom, "A slotted waveguide antenna employing resonant compound coupling slots for beam shaping," 1998 IEEE International Antennas and Propagation Symposium, Digest of papers, pp. 57 – 60; and R.V. Gatti, L. Marcaccioli, R. Sorrentino, "Design of slotted waveguide arrays with arbitrary complex slot voltage distribution," 2004 IEEE International Antennas and Propagation Symposium, Digest of papers, pp. 3265 - 3268, each of which is incorporated herein in its entirety). Arrays based on SIW have also been studied for this purpose as described by J.

Hirokawa and M. Ando, "40 GHz parallel-plate slot array fed by single layer waveguide consisting posts in a dielectric substrate," 1998 IEEE International Antennas and Propagation Symposium, Digest of papers, pp. 1698-1701 and S. Yang, S.H. Suleiman, A.E. Fathy, "Ku-band slot array antenna for low profile mobile DBS applications: printed vs. machined," 2006 IEEE International Antennas and Propagation Symposium, Digest of papers, pp 3137-3140. Although the efficiency of the SIW slot arrays is somewhat lower than the traditional metallic waveguide designs, they present affordable alternatives and are much more efficient than other planar technologies such as microstrip.

In an embodiment of HIMRA, the 2-D array may be constructed in the form of parallel slotted SIWs as shown in FIG. 7. Each waveguide may form one row in the array and be fed through the output port of a dedicated AFA device (MEMS phase-shifter chips **350)** (see FIG. 8C). The array beam, therefore, can be steered in the plane perpendicular to the waveguides by biasing the AFA elements to produce a linear phase delay profile across the rows. Antenna layer **100** may include antenna elements 110, H-plane Feed Lines 111, and coupling slots **500.**

Hybrid Integration

The integration of the feed network, slot array, and AFA chips to fabricate phased array antenna **10** may be performed in several steps of multilayer lamination as shown in FIGs 8A - 8C.

In the depicted embodiment, the adapter inner layer **300** is fabricated as a stack of two low-frequency substrate layers, first PCB layer **310** and second PCB layer **320** (e.g., using materials generally suitable for printed circuit board such as FR4 epoxy laminate material) with areas that may be equal to that of the array and the thicknesses equal to those of the MEMS cap and base wafers. Cavities (first cavities **331** and second cavities **332)** may be cut in both layers and sized to tightly fit the cascade AFA dies. Bias lines **340** may be etched on the surface of one of the boards and the two boards (first PCB layer **310** and second PCB layer **320)** stacked using a bonding film **400.** The sandwiched bias lines may be exposed in small regions that form the contact pads for the connection of the MEMS dies as well as the external control dies (FIG 8A). MEMS chips **350** may then be embedded in the cavities **330** (formed from first cavities **331** and cavities **332)** and bonded to the bias pads using, for example, conductive epoxy, although other materials and methods for attaching the chips may be used. The top and bottom slots of the AFA devices (MEMS phase-shifter chips **350)** may align with the upper and lower surfaces of the adapter inner layer **300** (FIG. 8B). The removed regions (cavities **330)** in the adapter inner layer may provide space for the placement of the MEMS chips **350** within an accuracy adequate for most MEMS applications (for example, ±25 μm), resulting in a self-aligned assembly process. Electrical contact between bias lines in the PCB inner layer **340** and bias pads in the MEMS chip **353** may be made through conductive epoxy or solder. The SIW feed board **200,** MEMS loaded adapter inner layer **300,** and slot array board **100** may then be aligned and bonded together using two laminate bonding films **400** and by applying pressure at a specified temparature (for example, at 220^{0}C) (FIG. 8C).

FIG. 9 depicts an embodiment of the present methods for assembling a phased array antenna that includes the steps of: fabricating as a first planar structure an antenna layer including an array of antenna elements (step **902);** fabricating as a second planar structure a feed layer including a feed network (step **904);** fabricating an adapter inner layer including fabricating low-frequency printed circuit board (PCB) structure with a plurality of stepped-wall cavities formed in said PCB structure (step **906);** fabricating a plurality of MEMS phase-shifter chips (step **908);** inserting said MEMS phase shifter chips into the corresponding cavities of said adapter inner layer, positioned so that the stepped structure of said MEMS phase shifters fits within said stepped-wall cavities in said adapter inner layer (step **910);** and bonding said MEMS phase-shifter chips to bias pads exposed in said adapter inner layer (step **912).** Step **908** may include: fabricating a base substrate having metallization and a coupling slot on a lower surface of said base substrate and a plurality of bias lines, passive lumped elements, transmission line segments and resonators, and MEMS switches on an upper surface of said base substrate; and fabricating a cap substrate smaller in size than said base substrate and having metallization and a coupling slot on an upper surface of said cap substrate and a plurality of cavities etched on a lower surface of said cap substrate; where said base and cap substrates are stacked with said upper surface of said base substrate facing said lower surface of the cap substrate.

FIG. 10 depicts a method of delivering and extracting a radio frequency signal to and from a MEMS phase-shifter chip that includes the steps of: electromagnetically coupling said radio frequency signal into said MEMS phase-shifter chips through coupling slots in said cap substrates (step **1010)** and electromagnetically coupling said radio frequency signal out of said coupling slots in said base substrates (step 1012).

Conclusion

The disclosed embodiments provide a hybrid architecture for cost effective implementation of the electronically scanned antenna arrays that take advantage of high performance electromagnetically-coupled self-packaged RF MEMS devices for phase shifting and multi-layer PCB technology for the implementation of the RF feed, bias circuitry, and the antenna structure. The disclosed embodiments offer an inexpensive method for fabricating high-performance low-loss beam-steering solutions for applications in defense and automotive radars, wireless communications and satellite communication.

All of the methods disclosed and claimed herein can be executed without undue experimentation in light of the present disclosure. While the methods of this disclosure may have been described in terms of preferred embodiments, it will be apparent to those of ordinary skill in the art that variations may be applied to the methods and in the steps or in the sequence of steps of the method described herein without departing from the concept, spirit and scope of the disclosure. All such similar substitutes and modifications apparent to those skilled in the art are deemed to be within the spirit, scope, and concept of the disclosure as defined by the appended claims.

It should also be noted and understood that all publications, patents and patent applications mentioned in this specification and/or cited below are indicative of the level of skill in the art to which the invention pertains. All publications, patents and patent applications are herein incorporated by reference to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated by reference in its entirety.

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CLAIMS:

1. A phased array antenna comprising:

a multi-layer stack comprising:

an antenna layer including an array of antenna elements fabricated as a first planar structure;

a feed layer including a feed network fabricated as a second planar structure; and

an adapter inner layer including a low-frequency printed circuit board (PCB) structure with a plurality of cavities formed in said PCB structure; and

a plurality of MEMS phase-shifter chips positioned within said cavities in said adapter inner layer.

2. The phased array antenna according to claim 1 wherein the cavities formed in the PCB structures are stepped wall cavities.

3. The phased array antenna according to claim 1 wherein the adapter inner layer is positioned between the antenna layer and the feed layer.

4. The phased array antenna according to claim 3 wherein said antenna layer, feed layer and adapter inner layer are bonded to each other with an adhesive material.

5. The phased array antenna according to claim 3 wherein antenna layer, feed layer and adapter inner layer are bonded to each other by intermediate bonding films.

6. The phased array antenna according to claim 1 wherein said adapter inner layer comprises:

a first PCB layer with a plurality of first cavities of a first size;

a second PCB layer with a plurality of second cavities of a second size smaller than said first size; and

bias circuitry including a plurality of supply lines and a plurality of control lines, said supply lines and said control lines present in at least one side of at least one of said first PCB layer and said second PCB layer.

7. The phased array antenna according to claim 6 wherein said supply lines and said control lines are present in both sides of at least one of said first PCB layer and said second PCB layer.

8. The phased array antenna according to claim 6 wherein said supply lines and said control lines are present in at least one side of both of said first PCB layer and said second PCB layer.

9. The phased array antenna according to claim 6 wherein a difference in dimensions between said first cavities of said first size and said second cavities of said second size forms a stepped-wall cavity structure in said stacked adapter inner layer with portions of said bias circuitry exposed at a surface of steps constituting said stepped-wall structure.

10. The phased array antenna according to claim 1 wherein:

said antenna layer comprises a substrate integrated waveguide (SIW) slot array;

said feed layer comprises a low-loss SIW network; and

said antenna layer and said feed layer are coupled to said MEMS phase-shifter chips through coupling slots etched in walls of the SIW slot array and said SIW network.

11. The phased array antenna according to claim 1 wherein:

said antenna layer comprises slot-coupled microstrip patch antennas;

said feed layer comprises a microstrip network; and

said antenna layer and said feed layer are coupled to the MEMS phase-shifter chips through coupling slots etched in ground planes of said antenna and feed layers.

12. A phased array antenna comprising:

a three-layer stack of:

(i) an antenna layer including an array of antenna elements fabricated as a first planar structure;

(ii) a feed layer including a feed network fabricated as a second planar structure, and

(iii) an adapter inner layer including a low-frequency printed circuit board (PCB) structure with a plurality of stepped-wall cavities formed in said PCB structure; and

a plurality of MEMS phase-shifter chips positioned within said stepped-wall cavities in said adapter inner layer.

13. The phased array antenna according to claim 12 wherein said antenna layer is positioned on a top of said three-layer stack, said feed layer is positioned on a bottom of said three-layer

stack, and said adapter inner layer is positioned in a middle ot said three-layer stack between said antenna and feed layers.

14. The phased array antenna according to claim 13 wherein said antenna layer, feed layer and adapter inner layer are bonded to each other with an adhesive material.

15. The phased array antenna according to claim 13 wherein antenna layer, feed layer and adapter inner layer are bonded to each other by intermediate bonding films.

16. The phased array antenna according to claim 12 wherein said adapter inner layer comprises:

a top PCB layer with a plurality of cavities of a first size;

a bottom PCB layer with a plurality of cavities of a second size smaller than said first size; and

bias circuitry including a plurality of supply lines and a plurality of control lines, said supply lines and said control lines present in at least one side of at least one of said PCB layers.

17. The phased array antenna according to claim 16 wherein said supply lines and said control lines present in at both sides of at least one of said PCB layers in the adapter inner layer.

18. The phased array antenna according to claim 16 wherein said supply and control lines are present in at least one side of both of said PCB layers in the adapter inner layer.

19. The phased array antenna according to claim 16 wherein a difference in dimensions between said cavities of said first size and said cavities of said second size forms a stepped-wall cavity structure in said stacked adapter inner layer with portions of said bias circuitry exposed at a surface of steps constituting said stepped-wall structure.

20. The phased array antenna according to claim 12 wherein:

said antenna layer comprises a substrate integrated waveguide (SIW) slot array;

said feed layer comprises a low-loss SIW network; and

said antenna layer and said feed layer are coupled to said MEMS phase-shifter chips through coupling slots etched in walls of the SIW slot array and said SIW network.

21. The phased array antenna according to claim 12 wherein:

said antenna layer comprises slot-coupled microstrip patch antennas;

said feed layer comprises a microstrip network; and

said antenna layer and feed layer are coupled to the MEMS phase-shifter chips through coupling slots etched in ground planes of said antenna and feed layers.

22. The phased array antenna accoring to claim 12 wherein the MEMS phase-shifter chips are in the form of the form of reconfigurable AFA elements, each comprising:

a stack of two dielectric substrates including

a base substrate having metallization and a coupling slot on a lower surface of said base substrate and a plurality of bias lines, passive lumped elements, transmission line segments and resonators, and MEMS switches on an upper surface of said base substrate, and

a cap substrate smaller in size than said base substrate and having metallization and a coupling slot on an upper surface of said cap substrate and a plurality of cavities etched on a lower surface of said cap substrate,

said base and cap substrates stacked and bonded with said upper surface of said base substrate facing said lower surface of the cap substrate,

said cap substrate cavities enclosing and protecting against humidity and mechanical damage to said MEMS switches on said base substrate.

23. The phased array antenna according to claim 22 wherein said base and cap substrates are bonded to each other with an adhesive material.

24. The phased array antenna according to claim 22 wherein a difference in the sizes of the base and cap substrates provides in a stepped-wall chip structure, exposing bias pads formed by an extension of the bias lines on the upper surface of the base substrate.

25. A self-aligned method of assembling a phased array antenna including the steps of:

(i) fabricating as a first planar structure an antenna layer including an array of antenna elements;

(ii) fabricating as a second planar structure a feed layer including a feed network;

(iii) fabricating an adapter inner layer including fabricating low-frequency printed circuit board (PCB) structure with a plurality of stepped-wall cavities formed in said PCB structure;

(iv) fabricating a plurality of MEMS ohase-shifter chips including fabricating a base substrate having metallization and a coupling slot on a lower surface of said base substrate and a plurality of bias lines, passive lumped elements, transmission line segments and resonators, and MEMS switches on an upper surface of said base substrate, and

fabricating a cap substrate smaller in size than said base substrate and having metallization and a coupling slot on an upper surface of said cap substrate and a plurality of cavities etched on a lower surface of said cap substrate,

said base and cap substrates stacked with said upper surface of said base substrate facing said lower surface of the cap substrate; and

(v) inserting said MEMS phase shifter chips into the corresponding cavities of said adapter inner layer, positioned so that the stepped structure of said MEMS phase shifters fits within said stepped-wall cavities in said adapter inner layer.

26. The self-aligned method of assembling a phased array antenna according to claim 25 further comprising a step of bonding said MEMS phase-shifter chips to bias pads exposed in said adapter inner layer.

27. A method of delivering and extracting a radio frequency signal to and from a MEMS phase-shifter chip including:

electromagnetically coupling said radio frequency signal into said MEMS phase-shifter chips through coupling slots in said cap substrates, and

electromagnetically coupling said radio frequency signal out of said coupling slots in said base substrates.

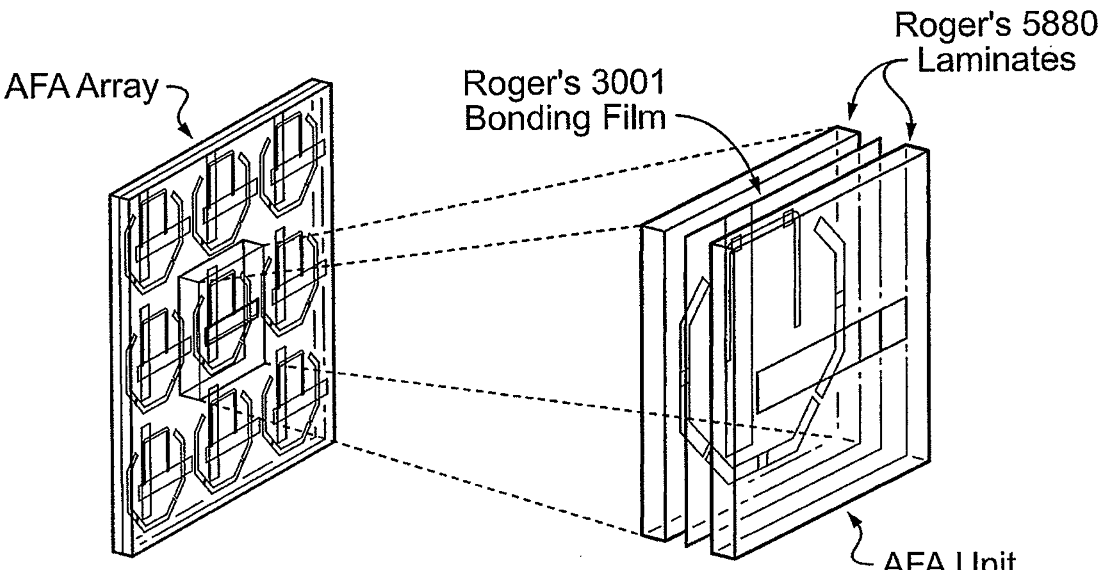

FIG. 1

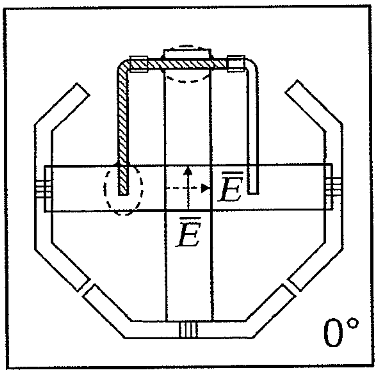

FIG. 2A

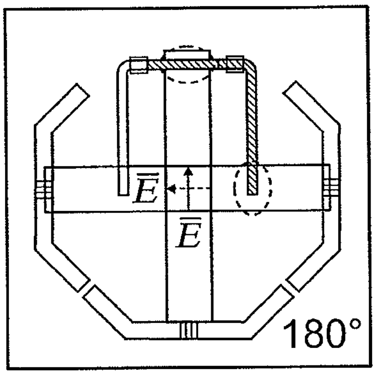

FIG. 2B

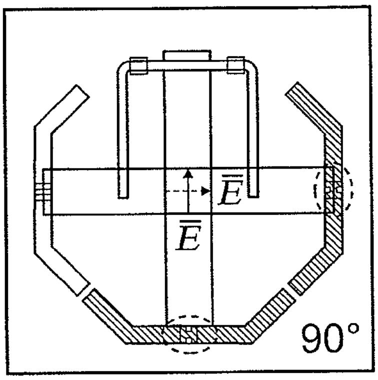

FIG. 2C

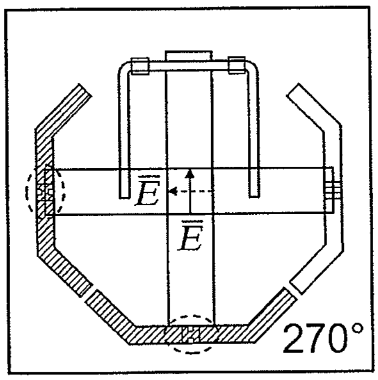

FIG. 2D

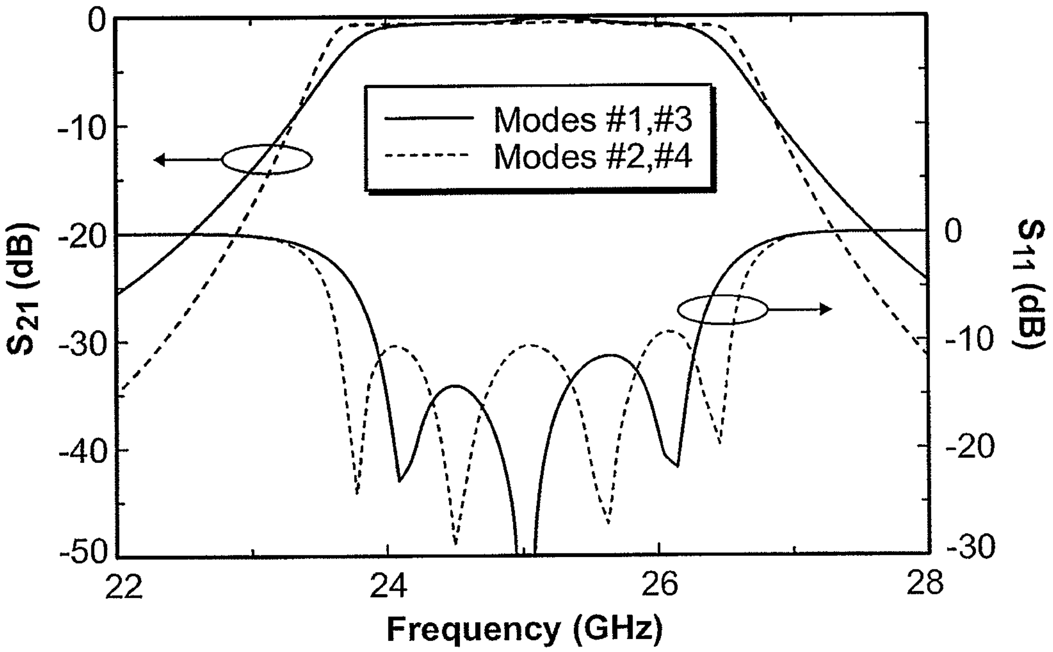
Modes #1,#3
Modes #2,#4
S21 (dB)
S11 (dB)
Frequency (GHz)
0
-10
-20
-30
-40
-50
22
24
26
28

FIG. 3

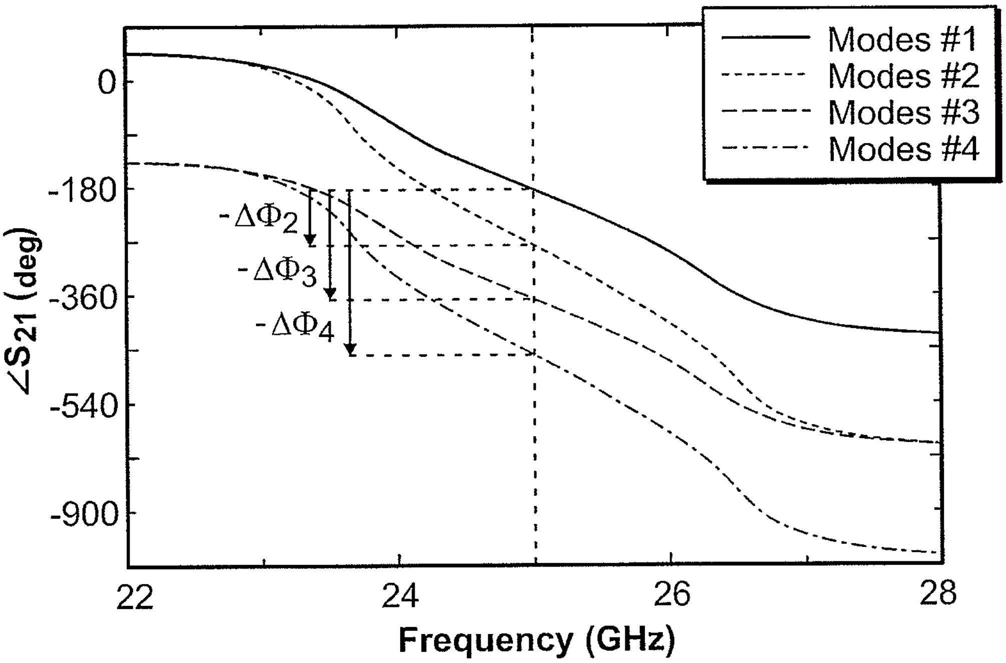
Modes #1
Modes #2
Modes #3
Modes #4
-ΔΦ2
-ΔΦ3
-ΔΦ4
∠S21 (deg)
Frequency (GHz)
0
-180
-360
-540
-900
22
24
26
28

FIG. 4

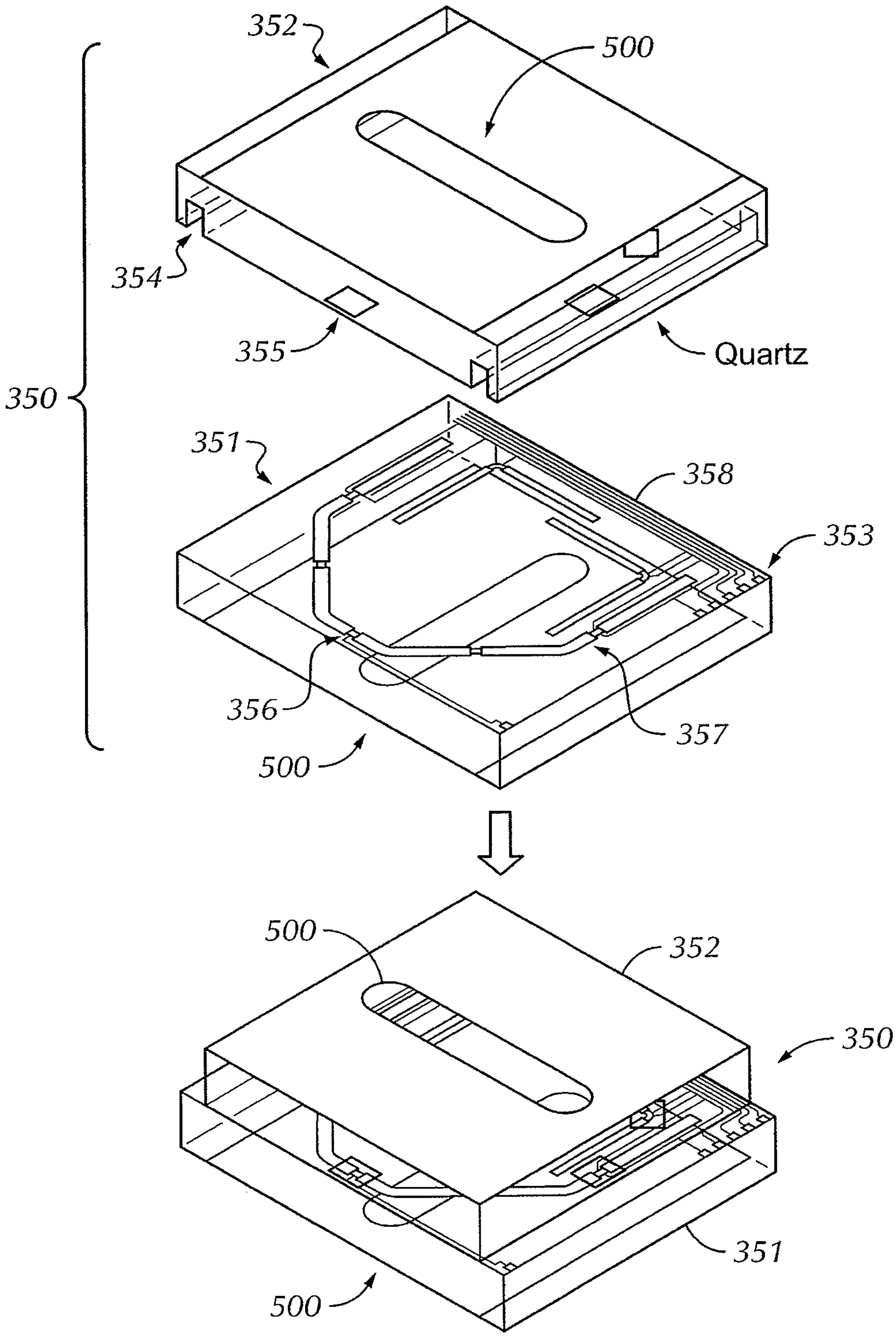
352
500
354
355
Quartz
350
351
358
353
356
357
500
500
352
350
351
500

FIG. 5

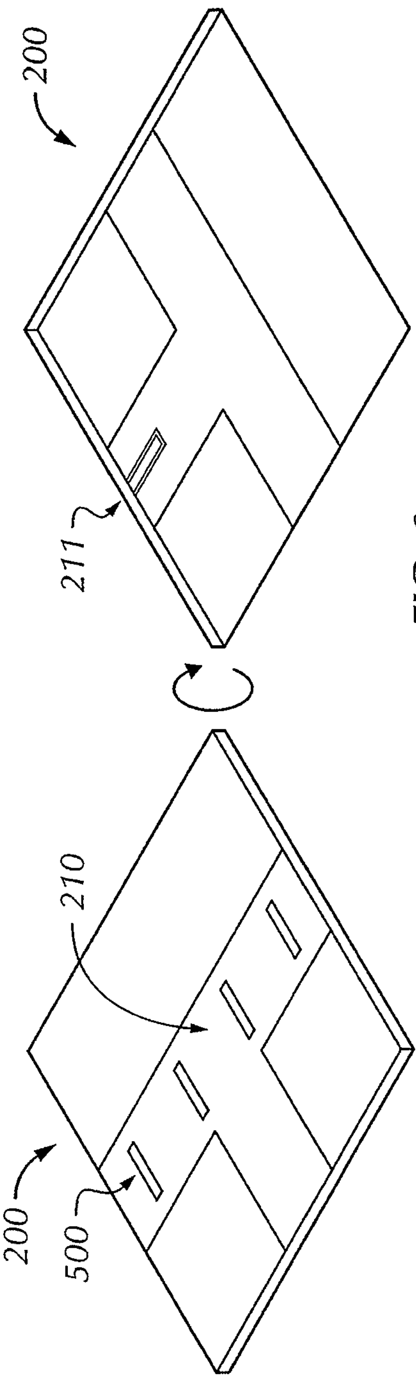
200
500
210
211
200

FIG. 6

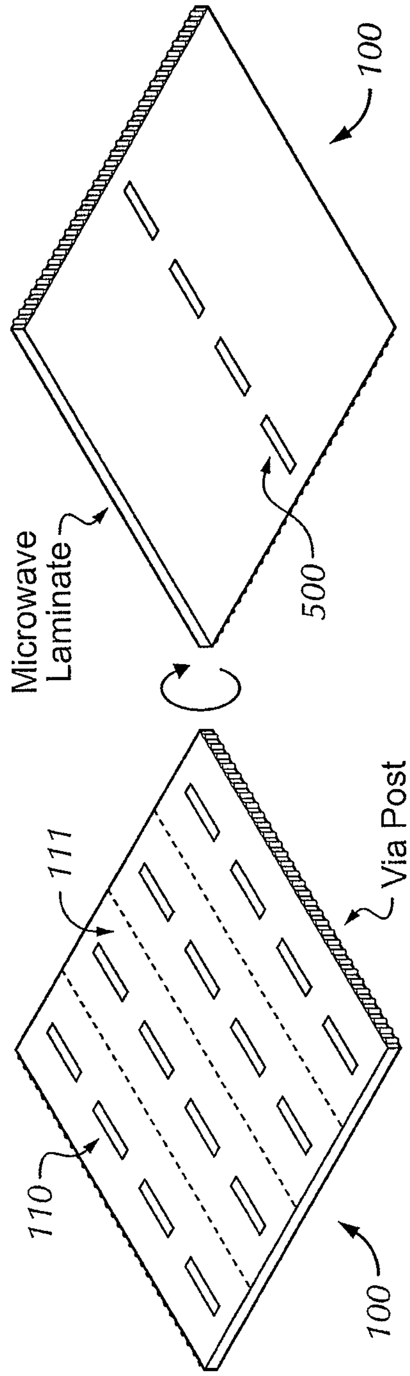
110
111
100
Via Post Wall
Microwave Laminate
500
100

FIG. 7

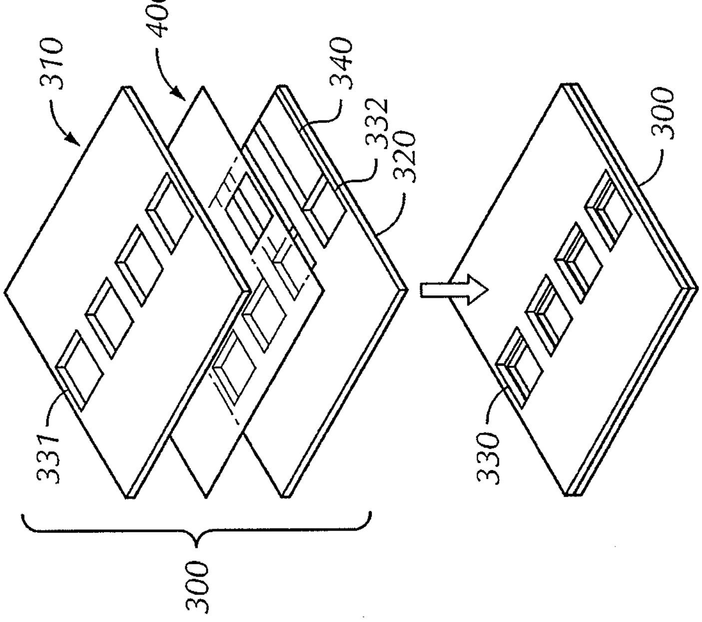

FIG. 8A

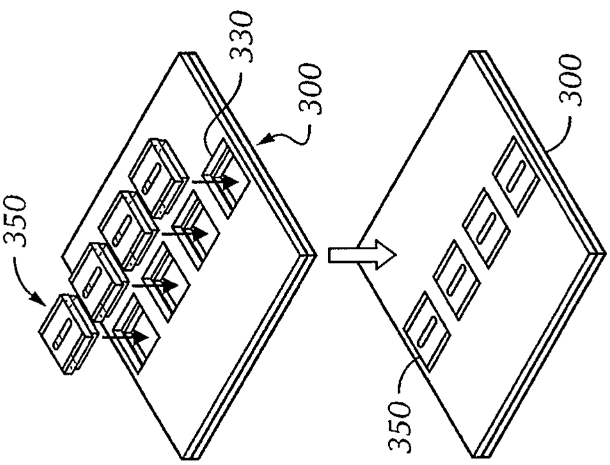

FIG. 8B

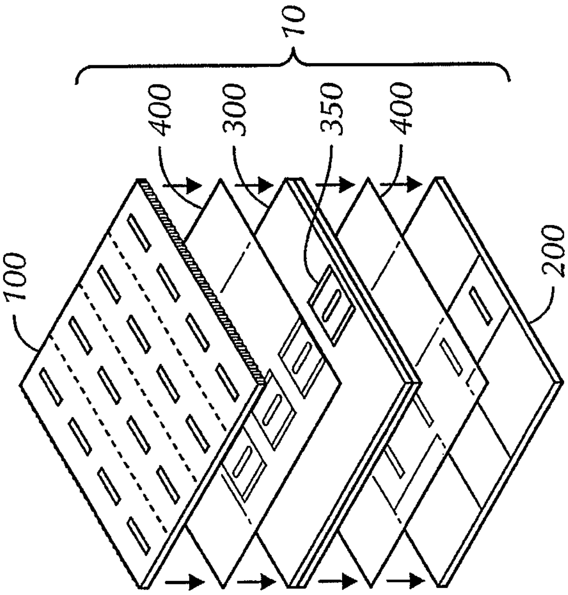

FIG. 8C

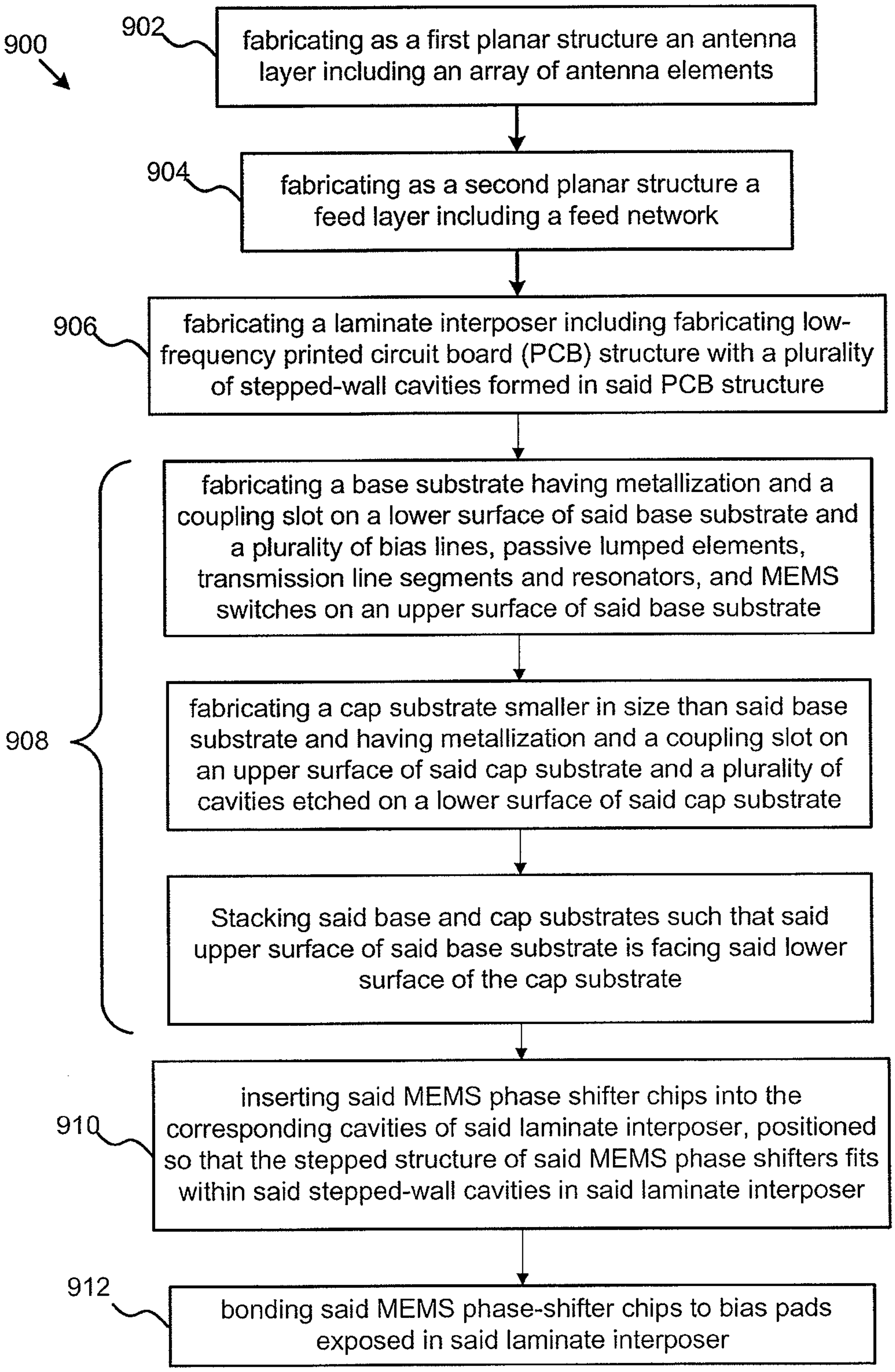
900
902
fabricating as a first planar structure an antenna layer including an array of antenna elements
904
fabricating as a second planar structure a feed layer including a feed network
906
fabricating a laminate interposer including fabricating low-frequency printed circuit board (PCB) structure with a plurality of stepped-wall cavities formed in said PCB structure
908
fabricating a base substrate having metallization and a coupling slot on a lower surface of said base substrate and a plurality of bias lines, passive lumped elements, transmission line segments and resonators, and MEMS switches on an upper surface of said base substrate
fabricating a cap substrate smaller in size than said base substrate and having metallization and a coupling slot on an upper surface of said cap substrate and a plurality of cavities etched on a lower surface of said cap substrate
Stacking said base and cap substrates such that said upper surface of said base substrate is facing said lower surface of the cap substrate
910
inserting said MEMS phase shifter chips into the corresponding cavities of said laminate interposer, positioned so that the stepped structure of said MEMS phase shifters fits within said stepped-wall cavities in said laminate interposer
912
bonding said MEMS phase-shifter chips to bias pads exposed in said laminate interposer

FIG. 9

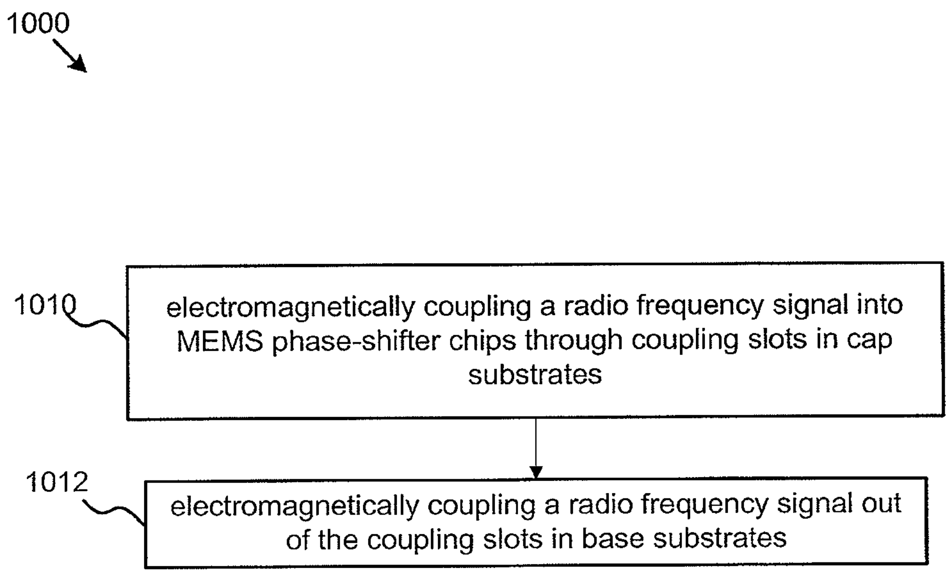
1000
1010
electromagnetically coupling a radio frequency signal into MEMS phase-shifter chips through coupling slots in cap substrates
1012
electromagnetically coupling a radio frequency signal out of the coupling slots in base substrates

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 08/72587

A CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01 Q 21/00 (2008.04)
USPC - 343/853
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)
USPC: 343/853

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 343/853, 909, 778, 700, 850, 776

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PUbWEST(PGPB, USPT, USOC, EPAB, JPAB); GOOGLE
Search Terms Used: Phase array antenna, MEMS phase-shifter, antenna layer, feed layer, chips, stepped wall cavities, printed circuit board, control and supply lines.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 6,297,774 B1 (Chung) 02 October 2001 (02.10.2001), entire document, especially; abstract, Col. 1 ln 9-13; Col. 1 ln - Col. 2 ln 15; Col. 5 ln 50-55.	1-27
Y	US 2003/0184476 A1 (Sikina et al.) 02 October 2003 (02.10.2003), entire document, especially; abstract, para [0003], [0010], [0046], [0068], [0054], [0058], [0060], [0063], [0070], [0107].	1-27
Y	US 5,135,341 A (Leyder) 04 August 1992 (04.08.1992), entire document, especially; abstract, Col. 1 ln 56 -Col. 2 ln 2.	2, 9, 19, 24-26
Y	US 2007/0153512 A1 (Hend πe) 05 July 2007 (05.07.2007), entire document, especially; abstract, para. [0025], [0039].	6-9, 16-19
Y	US 2004/0245548 A1 (Stockmeier et al.) 09 December 2004 (09.12.2004), entire document, especially; abstract, para. [0022], [0023].	22-26

☐ Further documents are listed in the continuation of Box C ☐

* Special categories of cited documents
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent 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
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 October 2008 (23.10.2008)	03 NOV 200B

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Lee W. Young PCT Helpdesk 571-272-4300 PCT OSP 571-272-7774