

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
23 March 2006 (23.03.2006)

PCT

(10) International Publication Number
WO 2006/031341 A2

(51) International Patent Classification:
H01Q 1/38 (2006.01)

(21) International Application Number:
PCT/US2005/028662

(22) International Filing Date: 11 August 2005 (11.08.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/522,077 11 August 2004 (11.08.2004) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

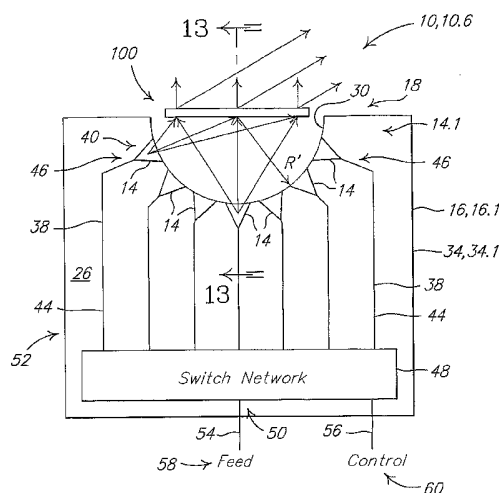
(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— without international search report and to be republished upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: MULTI-BEAM ANTENNA



(57) Abstract: A plurality of antenna end-fire antenna feed elements (14, 14.1) disposed along a contour (30) on a dielectric substrate (16) cooperate with a discrete lens array (100). An electromagnetic wave (20) launched by an antenna feed element (14, 14.1) is received by a first set of patch antennas (102.1) on a first side (104) of the discrete lens array (100), and the associated received signals are propagated through associated delay elements (108) to a corresponding second set of patch antennas (102.2) on the opposite side (106) of the discrete lens array (100) from which the associated received signals are reradiated, wherein the corresponding delays of the associated delay elements (108) are location dependent so as to emulate a dielectric electromagnetic lens (12) and thereby provide for forming an associated beam of electromagnetic energy (20). A signal applied to a corporate feed port (54) is switched to the antenna feed elements (14, 14.1) by a switching network (48), whereby different antenna feed elements (14, 14.1) generate different beams (20) of electromagnetic energy in different directions (42).

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MULTI-BEAM ANTENNA

CROSS-REFERENCE TO RELATED APPLICATIONS

The instant application claims the benefit of prior U.S. Provisional Application Serial No. **60/522,077** filed on **August 11, 2004**, which is incorporated herein by reference. The instant application is a continuation-in-part of U.S. Application Serial No. **10/604,716**, filed on **August 12, 2003**, which is a continuation-in-part of U.S. Application Serial No. **10/202,242**, filed on **July 23, 2002**, now U.S. Patent No. **6,606,077**, which is a continuation-in-part of U.S. Application Serial No. **09/716,736**, filed on **November 20, 2000**, now U.S. Patent No. **6,424,319**, which claims the benefit of U.S. Provisional Application Serial No. **60/166,231** filed on **November 18, 1999**, all of which are incorporated herein by reference. The instant application is related in part in subject matter to U.S. Application Serial No. **10/907,305**, filed on **March 28, 2005**, which is incorporated herein by reference.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings:

FIG. 1 illustrates a top view of a first embodiment of a multi-beam antenna comprising an electromagnetic lens;

FIG. 2 illustrates a fragmentary side cross-sectional view of the embodiment illustrated in **FIG. 1**;

FIG. 3 illustrates a fragmentary side cross-sectional view of the embodiment illustrated in **FIG. 1**, incorporating a truncated electromagnetic lens;

FIG. 4 illustrates a fragmentary side cross-sectional view of an embodiment illustrating various locations of a dielectric substrate, relative to an electromagnetic lens;

FIG. 5 illustrates an embodiment of a multi-beam antenna, wherein each antenna feed element is operatively coupled to a separate signal;

FIG. 6 illustrates an embodiment of a multi-beam antenna, wherein the associated switching network is separately located from the dielectric substrate;

FIG. 7 illustrates a top view of a second embodiment of a multi-beam antenna comprising a plurality of electromagnetic lenses located proximate to one edge of a dielectric substrate;

FIG. 8 illustrates a top view of a third embodiment of a multi-beam antenna comprising a plurality of electromagnetic lenses located proximate to opposite edges of a dielectric substrate;

FIG. 9 illustrates a side view of the third embodiment illustrated in **FIG. 8**, further comprising a plurality of reflectors;

FIG. 10 illustrates a fourth embodiment of a multi-beam antenna, comprising an electromagnetic lens and a reflector;

FIG. 11 illustrates a fifth embodiment of a multi-beam antenna;

FIG. 12 illustrates a top view of a sixth embodiment of a multi-beam antenna comprising a discrete lens array;

FIG. 13 illustrates a fragmentary side cross-sectional view of the embodiment illustrated in **FIG. 12**;

FIG. 14 illustrates a block diagram of a discrete lens array;

FIG. 15a illustrates a first side of one embodiment of a planar discrete lens array;

FIG. 15b illustrates a second side of one embodiment of a planar discrete lens array;

FIG. 16 illustrates a plot of delay as a function of radial location on the planar discrete array illustrated in **FIGS. 15a and 15b**;

FIG. 17 illustrates a fragmentary cross sectional isometric view of a first embodiment of a discrete lens antenna element;

FIG. 18 illustrates an isometric view of the first embodiment of a discrete lens antenna element illustrated in **FIG. 17**, isolated from associated dielectric substrates;

FIG. 19 illustrates an isometric view of a second embodiment of a discrete lens antenna element;

FIG. 20 illustrates an isometric view of a third embodiment of a discrete lens antenna element, isolated from associated dielectric substrates;

FIG. 21 illustrates a cross sectional view of the third embodiment of the discrete lens antenna element;

FIG. 22 illustrates a plan view of a second embodiment of a discrete lens array;

FIG. 23 illustrates an isometric view of a fourth embodiment of a discrete lens antenna element, isolated from associated dielectric substrates;

FIG. 24a illustrates a cross sectional view of the fourth embodiment of the discrete lens antenna element of a third embodiment of a discrete lens array;

5 **FIG. 24b** illustrates a cross sectional view of the fourth embodiment of a discrete lens antenna element of a fourth embodiment of a discrete lens array;

FIG. 25 illustrates a fragmentary cross sectional isometric view of a fifth embodiment of a discrete lens antenna element of a reflective discrete lens array;

10 **FIG. 26** illustrates a seventh embodiment of a multi-beam antenna, comprising a discrete lens array and a reflector; and

FIG. 27 illustrates an eighth embodiment of a multi-beam antenna.

DETAILED DESCRIPTION OF EMBODIMENT(S)

Referring to **FIGS. 1 and 2**, a **multi-beam antenna 10, 10.1** comprises at least one **electromagnetic lens 12** and a plurality of **antenna feed elements 14** on a **dielectric substrate 16** proximate to a **first edge 18** thereof, wherein the plurality of **antenna feed elements 14** are adapted to radiate or receive a corresponding plurality of **beams of electromagnetic energy 20** through the at least one **electromagnetic lens 12**.

The at least one **electromagnetic lens 12** has a **first side 22** having a **first contour 24** at an intersection of the **first side 22** with a **reference surface 26**, for example, a **plane 26.1**.

20 The at least one **electromagnetic lens 12** acts to diffract the electromagnetic wave from the respective **antenna feed elements 14**, wherein different **antenna feed elements 14** at different locations and in different directions relative to the at least one **electromagnetic lens 12** generate different associated different **beams of electromagnetic energy 20**. The at least one **electromagnetic lens 12** has a **refractive index n** different from free space, for example,

25 a **refractive index n** greater than one (1). For example, the at least one **electromagnetic lens 12** may be constructed of a material such as REXOLITE™, TEFLON™, polyethylene, polystyrene or some other dielectric; or a plurality of different materials having different refractive indices, for example as in a Luneburg lens. In accordance with known principles of diffraction, the shape and size of the at least one **electromagnetic lens 12**, the **refractive index n** thereof, and the relative position of the **antenna feed elements 14** to the

30 **electromagnetic lens 12** are adapted in accordance with the radiation patterns of the **antenna**

feed elements 14 to provide a desired pattern of radiation of the respective beams of electromagnetic energy 20 exiting the second side 28 of the at least one electromagnetic lens 12. Whereas the at least one electromagnetic lens 12 is illustrated as a spherical lens 12' in FIGS. 1 and 2, the at least one electromagnetic lens 12 is not limited to any one particular design, and may, for example, comprise either a spherical lens, a Luneburg lens, a spherical shell lens, a hemispherical lens, an at least partially spherical lens, an at least partially spherical shell lens, an elliptical lens, a cylindrical lens, or a rotational lens. Moreover, one or more portions of the electromagnetic lens 12 may be truncated for improved packaging, without significantly impacting the performance of the associated multi-beam antenna 10, 10.1. For example, FIG. 3 illustrates an at least partially spherical electromagnetic lens 12'' with opposing first 27 and second 29 portions removed therefrom.

The first edge 18 of the dielectric substrate 16 comprises a second contour 30 that is proximate to the first contour 24. The first edge 18 of the dielectric substrate 16 is located on the reference surface 26, and is positioned proximate to the first side 22 of one of the at least one electromagnetic lens 12. The dielectric substrate 16 is located relative to the electromagnetic lens 12 so as to provide for the diffraction by the at least one electromagnetic lens 12 necessary to form the beams of electromagnetic energy 20. For the example of a multi-beam antenna 10 comprising a planar dielectric substrate 16 located on reference surface 26 comprising a plane 26.1, in combination with an electromagnetic lens 12 having a center 32, for example, a spherical lens 12'; the plane 26.1 may be located substantially close to the center 32 of the electromagnetic lens 12 so as to provide for diffraction by at least a portion of the electromagnetic lens 12. Referring to FIG. 4, the dielectric substrate 16 may also be displaced relative to the center 32 of the electromagnetic lens 12, for example on one or the other side of the center 32 as illustrated by dielectric substrates 16' and 16'', which are located on respective reference surfaces 26' and 26''.

The dielectric substrate 16 is, for example, a material with low loss at an operating frequency, for example, DUROID™, a TEFLON™ containing material, a ceramic material, or a composite material such as an epoxy/fiberglass composite. Moreover, in one embodiment, the dielectric substrate 16 comprises a dielectric 16.1 of a circuit board 34, for example, a printed circuit board 34.1 comprising at least one conductive layer 36 adhered to the dielectric substrate 16, from which the antenna feed elements 14 and other

associated **circuit traces 38** are formed, for example, by subtractive technology, for example, chemical or ion etching, or stamping; or additive techniques, for example, deposition, bonding or lamination.

The plurality of **antenna feed elements 14** are located on the **dielectric substrate 16** along the **second contour 30** of the **first edge 18**, wherein each **antenna feed element 14** comprises a least one **conductor 40** operatively connected to the **dielectric substrate 16**. For example, at least one of the **antenna feed elements 14** comprises an **end-fire antenna element 14.1** adapted to launch or receive electromagnetic waves in a **direction 42** substantially towards or from the **first side 22** of the at least one **electromagnetic lens 12**, wherein different **end-fire antenna elements 14.1** are located at different locations along the **second contour 30** so as to launch or receive respective electromagnetic waves in different **directions 42**. An **end-fire antenna element 14.1** may, for example, comprise either a Yagi-Uda antenna, a coplanar horn antenna (also known as a tapered slot antenna), a Vivaldi antenna, a tapered dielectric rod, a slot antenna, a dipole antenna, or a helical antenna, each of which is capable of being formed on the **dielectric substrate 16**, for example, from a **printed circuit board 34.1**, for example, by subtractive technology, for example, chemical or ion etching, or stamping; or additive techniques, for example, deposition, bonding or lamination. Moreover, the **antenna feed elements 14** may be used for transmitting, receiving or both transmitting and receiving.

Referring to **FIG. 4**, the **direction 42** of the one or more **beams of electromagnetic energy 20, 20', 20''** through the **electromagnetic lens 12, 12'** is responsive to the relative location of the **dielectric substrate 16, 16' or 16''** and the associated **reference surface 26, 26' or 26''** relative to the **center 32** of the **electromagnetic lens 12**. For example, with the **dielectric substrate 16** substantially aligned with the **center 32**, the **directions 42** of the one or more **beams of electromagnetic energy 20** are nominally aligned with the **reference surface 26**. Alternately, with the **dielectric substrate 16'** above the **center 32** of the **electromagnetic lens 12, 12'**, the resulting one or more **beams of electromagnetic energy 20'** propagate in **directions 42'** below the **center 32**. Similarly, with the **dielectric substrate 16''** below the **center 32** of the **electromagnetic lens 12, 12'**, the resulting one or more **beams of electromagnetic energy 20''** propagate in **directions 42''** above the **center 32**.

The **multi-beam antenna 10** may further comprise at least one **transmission line 44** on the **dielectric substrate 16** operatively connected to a **feed port 46** of one of the plurality of **antenna feed elements 14**, for feeding a signal to the associated **antenna feed element**

14. For example, the at least one **transmission line 44** may comprise either a stripline, a microstrip line, an inverted microstrip line, a slotline, an image line, an insulated image line, a tapped image line, a coplanar stripline, or a coplanar waveguide line formed on the **dielectric substrate 16**, for example, from a **printed circuit board 34.1**, for example, by
5 subtractive technology, for example, chemical or ion etching, or stamping; or additive techniques, for example, deposition, bonding or lamination.

The **multi-beam antenna 10** may further comprise a **switching network 48** having at least one **input 50** and a plurality of **outputs 52**, wherein the at least one **input 50** is operatively connected -- for example, via at least one above described **transmission line 44** -
10 - to a **corporate antenna feed port 54**, and each **output 52** of the plurality of **outputs 52** is connected -- for example, via at least one above described **transmission line 44** -- to a respective **feed port 46** of a different **antenna feed element 14** of the plurality of **antenna feed elements 14**. The **switching network 48** further comprises at least one **control port 56** for controlling which **outputs 52** are connected to the at least one **input 50** at a given time.
15 The **switching network 48** may, for example, comprise either a plurality of micro-mechanical switches, PIN diode switches, transistor switches, or a combination thereof, and may, for example, be operatively connected to the **dielectric substrate 16**, for example, by surface mount to an associated **conductive layer 36** of a **printed circuit board 34.1**.

In operation, a **feed signal 58** applied to the **corporate antenna feed port 54** is either
20 blocked -- for example, by an open circuit, by reflection or by absorption, -- or switched to the associated **feed port 46** of one or more **antenna feed elements 14**, via one or more associated **transmission lines 44**, by the **switching network 48**, responsive to a **control signal 60** applied to the **control port 56**. It should be understood that the **feed signal 58** may either comprise a single signal common to each **antenna feed element 14**, or a plurality of
25 signals associated with different **antenna feed elements 14**. Each **antenna feed element 14** to which the **feed signal 58** is applied launches an associated electromagnetic wave into the **first side 22** of the associated **electromagnetic lens 12**, which is diffracted thereby to form an associated **beam of electromagnetic energy 20**. The associated **beams of electromagnetic energy 20** launched by different **antenna feed elements 14** propagate in
30 different associated **directions 42**. The various **beams of electromagnetic energy 20** may be generated individually at different times so as to provide for a scanned **beam of electromagnetic energy 20**. Alternately, two or more **beams of electromagnetic energy 20** may be generated simultaneously. Moreover, different **antenna feed elements 14** may be

driven by different frequencies that, for example, are either directly switched to the respective **antenna feed elements 14**, or switched via an associated **switching network 48** having a plurality of **inputs 50**, at least some of which are connected to different **feed signals 58**.

Referring to **FIG. 5**, the **multi-beam antenna 10, 10.1** may be adapted so that the
5 respective signals are associated with the respective **antenna feed elements 14** in a one-to-one relationship, thereby precluding the need for an associated **switching network 48**. For example, each **antenna feed element 14** can be operatively connected to an associated **signal 59** through an associated **processing element 61**. As one example, with the **multi-beam antenna 10, 10.1** configured as an imaging array, the respective **antenna feed elements 14**
10 are used to receive electromagnetic energy, and the respective **processing elements 61** comprise detectors. As another example, with the **multi-beam antenna 10, 10.1** configured as a communication antenna, the respective **antenna feed elements 14** are used to both transmit and receive electromagnetic energy, and the respective **processing elements 61** comprise transmit/receive modules or transceivers.

15 Referring to **FIG. 6**, the **switching network 48**, if used, need not be collocated on a common **dielectric substrate 16**, but can be separately located, as, for example, may be useful for low frequency applications, for example, for operating frequencies less than **20 GHz**, e.g. **1-20 GHz**.

Referring to **FIGS. 7, 8 and 9**, in accordance with a second aspect, a **multi-beam antenna 10'** comprises at least **first 12.1 and second 12.2 electromagnetic lenses**, each
20 having a **first side 22.1, 22.2** with a corresponding **first contour 24.1, 24.2** at an intersection of the respective **first side 22.1, 22.2** with the **reference surface 26**. The **dielectric substrate 16** comprises at least a **second edge 62** comprising a **third contour 64**, wherein the **second contour 30** is proximate to the **first contour 24.1** of the **first electromagnetic lens 12.1** and the **third contour 64** is proximate to the **first contour 24.2** of the **second electromagnetic lens 12.2**.
25

Referring to **FIG. 7**, in accordance with a second embodiment of the **multi-beam antenna 10.2**, the **second edge 62** is the same as the **first edge 18** and the **second 30 and third 64 contours** are displaced from one another along the **first edge 18** of the **dielectric substrate 16**.
30

Referring to **FIG. 8**, in accordance with a third embodiment of the **multi-beam antenna 10.3**, the **second edge 62** is different from the **first edge 18**, and more particularly is opposite to the **first edge 18** of the **dielectric substrate 16**.

Referring to **FIG. 9**, in accordance with a third aspect, a **multi-beam antenna 10''**
5 comprises at least one **reflector 66**, wherein the **reference surface 26** intersects the at least one **reflector 66** and one of the at least one **electromagnetic lens 12** is located between the **dielectric substrate 16** and the **reflector 66**. The at least one **reflector 66** is adapted to reflect electromagnetic energy propagated through the at least one **electromagnetic lens 12** after being generated by at least one of the plurality of **antenna feed elements 14**. The third
10 embodiment of the **multi-beam antenna 10** comprises at least **first 66.1** and **second 66.2** **reflectors** wherein the **first electromagnetic lens 12.1** is located between the **dielectric substrate 16** and the **first reflector 66.1**, the **second electromagnetic lens 12.2** is located between the **dielectric substrate 16** and the **second reflector 66.2**, the **first reflector 66.1** is adapted to reflect electromagnetic energy propagated through the **first electromagnetic lens**
15 **12.1** after being generated by at least one of the plurality of **antenna feed elements 14** on the **second contour 30**, and the **second reflector 66.2** is adapted to reflect electromagnetic energy propagated through the **second electromagnetic lens 12.2** after being generated by at least one of the plurality of **antenna feed elements 14** on the **third contour 64**. For example, the **first 66.1** and **second 66.2** **reflectors** may be oriented to direct the **beams of**
20 **electromagnetic energy 20** from each side in a common nominal direction, as illustrated in **FIG. 9**. Referring to **FIG. 9**, the **multi-beam antenna 10''** as illustrated would provide for scanning in a direction normal to the plane of the illustration. If the **dielectric substrate 16** were rotated by **90** degrees with respect to the **reflectors 66.1, 66.2**, about an axis connecting the respective **electromagnetic lenses 12.1, 12.1**, then the **multi-beam antenna 10''** would
25 provide for scanning in a direction parallel to the plane of the illustration.

Referring to **FIG. 10**, in accordance with the third aspect and a fourth embodiment, a **multi-beam antenna 10''**, **10.4** comprises an at least partially spherical **electromagnetic lens 12'''**, for example, a hemispherical electromagnetic lens, having a **curved surface 68** and a **boundary 70**, for example a **flat boundary 70.1**. The **multi-beam antenna 10''**, **10.4**
30 further comprises a **reflector 66** proximate to the **boundary 70**, and a plurality of **antenna feed elements 14** on a **dielectric substrate 16** proximate to a **contoured edge 72** thereof, wherein each of the **antenna feed elements 14** is adapted to radiate a respective plurality of **beams of electromagnetic energy 20** into a **first sector 74** of the **electromagnetic lens**

12'''. The **electromagnetic lens 12'''** has a **first contour 24** at an intersection of the **first sector 74** with a **reference surface 26**, for example, a **plane 26.1**. The **contoured edge 72** has a **second contour 30** located on the **reference surface 26** that is proximate to the **first contour 24** of the **first sector 74**. The **multi-beam antenna 10''**, 10.4 further comprises a
5 **switching network 48** and a plurality of **transmission lines 44** operatively connected to the **antenna feed elements 14** as described hereinabove for the other embodiments.

In operation, at least one **feed signal 58** applied to a **corporate antenna feed port 54** is either blocked, or switched to the associated **feed port 46** of one or more **antenna feed elements 14**, via one or more associated **transmission lines 44**, by the **switching network 48**
10 responsive to a **control signal 60** applied to a **control port 56** of the **switching network 48**. Each **antenna feed element 14** to which the **feed signal 58** is applied launches an associated electromagnetic wave into the **first sector 74** of the associated **electromagnetic lens 12'''**. The electromagnetic wave propagates through -- and is diffracted by -- the **curved surface 68**, and is then reflected by the **reflector 66** proximate to the **boundary 70**, whereafter the
15 reflected electromagnetic wave propagates through the **electromagnetic lens 12'''** and exits - - and is diffracted by -- a **second sector 76** as an associated **beam of electromagnetic energy 20**. With the **reflector 66** substantially normal to the **reference surface 26** -- as illustrated in **FIG. 10** -- the different **beams of electromagnetic energy 20** are directed by the associated **antenna feed elements 14** in different directions that are nominally substantially parallel to
20 the **reference surface 26**.

Referring to **FIG. 11**, in accordance with a fourth aspect and a fifth embodiment, a **multi-beam antenna 10'''**, 10.5 comprises an **electromagnetic lens 12** and plurality of **dielectric substrates 16**, each comprising a set of **antenna feed elements 14** and operating in accordance with the description hereinabove. Each set of **antenna feed elements 14**
25 generates (or is capable of generating) an associated set of **beams of electromagnetic energy 20.1, 20.2 and 20.3**, each having associated **directions 42.1, 42.2 and 42.3**, responsive to the associated **feed 58 and control 60 signals**. The associated **feed 58 and control 60 signals** are either directly applied to the associated **switch network 48** of the respective sets of **antenna feed elements 14**, or are applied thereto through a **second switch network 78**
30 having associated **feed 80 and control 82 ports**, each comprising at least one associated signal. Accordingly, the **multi-beam antenna 10'''**, 10.5 provides for transmitting or receiving one or more beams of electromagnetic energy over a three-dimensional space.

The **multi-beam antenna 10** provides for a relatively wide field-of-view, and is suitable for a variety of applications, including but not limited to automotive radar, point-to-point communications systems and point-to-multi-point communication systems, over a wide range of frequencies for which the **antenna feed elements 14** may be designed to radiate, for example, frequencies in the range of **1 to 200 GHz**. Moreover, the **multi-beam antenna 10** may be configured for either mono-static or bi-static operation.

When relatively a narrow beamwidth, i.e. a high gain, is desired at a relatively lower frequency, a dielectric **electromagnetic lens 12** can become relatively large and heavy. Generally, for these and other operating frequencies, the dielectric **electromagnetic lens 12** may be replaced with a **discrete lens array 100**, e.g. a **planar lens 100.1**, which can beneficially provide for setting the polarization, the ratio of focal length to diameter, and the focal surface shape, and can be more readily be made to conform to a surface. A **discrete lens array 100** can also be adapted to incorporate amplitude weighting so as to provide for control of sidelobes in the associates **beams of electromagnetic energy 20**.

For example, referring to **FIGS. 12 and 13**, in accordance with the first aspect and a sixth embodiment of a **multi-beam antenna 10, 10.6**, the dielectric **electromagnetic lens 12** of the first embodiment of the **multi-beam antenna 10, 10.1** illustrated in **FIGS. 1 and 2** is replaced with a **planar lens 100.1** comprising a **first set of patch antennas 102.1** on a **first side 104** of the **planar lens 100.1**, and a **second set of patch antennas 102.2** on the **second side 106** of the **planar lens 100.1**, where the **first 104 and second 106 sides** are opposite one another. The individual **patch antennas 102** of the **first 102.1 and second 102.2 sets of patch antennas** are in one-to-one correspondence. Referring to **FIG. 14**, each **patch antenna 102, 102.1** on the **first side 104** of the **planar lens 100.1** is operatively coupled via a **delay element 108** to a corresponding **patch antenna 102, 102.2** on the **second side 106** of the **planar lens 100.1**, wherein the **patch antenna 102, 102.1** on the **first side 104** of the **planar lens 100.1** is substantially aligned with the corresponding **patch antenna 102, 102.2** on the **second side 106** of the **planar lens 100.1**.

In operation, electromagnetic energy that is radiated upon one of the **patch antennas 102**, e.g. a **first patch antenna 102.1** on the **first side 104** of the **planar lens 100.1**, is received thereby, and a signal responsive thereto is coupled via -- and delayed by -- the **delay element 108** to the corresponding **patch antenna 102**, e.g. the **second patch antenna 102.2**, wherein the amount of delay by the **delay element 108** is dependent upon the location of the corresponding **patch antennas 102** on the respective **first 104 and second 106 sides** of the

planar lens 100.1. The signal coupled to the **second patch antenna 102.2** is then radiated thereby from the **second side 106** of the **planar lens 100.1**. Stated in another way, the **planar lens 100.1** comprises a plurality of **lens elements 110**, wherein each **lens element 110** comprises a **first patch antenna element 102.1** operatively coupled to a corresponding
5 **second patch antenna element 102.2** via at least one **delay element 108**, wherein the **first 102.1** and **second 102.2 patch antenna elements** are substantially opposed to one another on opposite sides of the **planar lens 100.1**.

Referring also to **FIGS. 15a and 15b**, in a first embodiment of a **planar lens 100.1**, the **patch antennas 102.1, 102.2** comprise conductive surfaces on a **dielectric substrate 112**,
10 and the **delay element 108** coupling the **patch antennas 102.1, 102.2** of the **first 104** and **second 106** sides of the **planar lens 100.1** comprise **delay lines 114**, e.g. microstrip or stripline structures, that are located adjacent to the associated **patch antennas 102.1, 102.2** on the underlying **dielectric substrate 112**. The **first ends 116.1** of the **delay lines 114** are connected to the corresponding **patch antennas 102.1, 102.2**, and the **second ends 116.2** of
15 the **delay lines 114** are interconnected to one another with a conductive path, for example, with a **conductive via 118** through the **dielectric substrate 112**. **FIGS. 15a and 15b** illustrate the **delay lines 114** arranged so as to provide for feeding the associated **first 102.1** and **second 102.2 sets of patch antennas** at the same relative locations.

Referring to **FIG. 16**, the amount of delay caused by the associated **delay elements 108** is made dependent upon the location of the associated **patch antenna 102** in the **planar lens 100.1**, and, for example, is set by the length of the associated **delay lines 114**, as illustrated by the configuration illustrated in **FIGS. 15a and 15b**, so as to emulate the phase properties of a convex **electromagnetic lens 12**, e.g. a **spherical lens 12'**. The shape of the delay profile illustrated in **FIG. 16** can be of various configurations, for example, 1) uniform
20 for all radial directions, thereby emulating a **spherical lens 12'**; 2) adapted to incorporate an azimuthal dependence, e.g. so as to emulate an elliptical lens; or 3) adapted to provide for focusing in one direction only, e.g. in the elevation plane of the **multi-beam antenna 10.6**, e.g. so as to emulate a cylindrical lens.

Referring to **FIGS. 17 and 18**, a first embodiment of a **lens element 110^I** of the
30 **planar lens 100.1** illustrated in **FIGS. 15a and 15b** comprises **first 102.1** and **second 102.2 patch antenna elements** on the outer surfaces of a **core assembly 120** comprising **first 112.1** and **second 112.2 dielectric substrates** on both sides of a **conductive ground plane 122** sandwiched therebetween. A **first delay line 114.1** on the **first side 104** of the **planar**

lens **100.1** extends circumferentially from a **first location 124.1** on the periphery of the **first patch antenna element 102.1** to a **first end 118.1** of a **conductive via 118** extending through the **core assembly 120**, and a **second delay line 114.2** on the **second side 106** of the **planar lens 100.1** extends circumferentially from a **second location 124.2** on the periphery of the **second patch antenna element 102.2** to a **second end 118.2** of the **conductive via 118**. Accordingly, the combination of the **first 114.1 and second 114.2 delay lines** interconnected by the **conductive via 118** constitutes the associated **delay element 108** of the **lens element 110**, and the amount of delay of the **delay element 108** is generally responsive to the cumulative circumferential lengths of the associated **first 114.1 and second 114.2 delay lines** and the **conductive via 118**. For example, the **delay element 108** may comprise at least one transmission line comprising either a stripline, a microstrip line, an inverted microstrip line, a slotline, an image line, an insulated image line, a tapped image line, a coplanar stripline, or a coplanar waveguide line formed on the **dielectric substrate(s) 112, 112.1, 112.2**, for example, from a printed circuit board, for example, by subtractive technology, for example, chemical or ion etching, or stamping; or additive techniques, for example, deposition, bonding or lamination.

Referring to **FIG. 19**, in accordance with a second embodiment of a **lens element 110^{II}** of the **planar lens 100.1**, the **first 102.1 and second 102.2 patch antenna elements** may be interconnected with one another so as to provide for dual polarization, for example, as disclosed in the technical paper "Multibeam Antennas with Polarization and Angle Diversity" by Darko Popovic and Zoya Popovic in *IEEE Transactions on Antenna and Propagation*, Vol. 50, No. 5, May 2002, which is incorporated herein by reference. A **first location 126.1** on an edge of the **first patch antenna element 102.1** is connected via **first 128.1 and second 128.2 delay lines** to a **first location 130.1** on the **second patch antenna element 102.2**, and a **second location 126.2** on an edge of the **first patch antenna element 102.1** is connected via **third 128.3 and fourth 128.4 delay lines** to a **second location 130.2** on the **second patch antenna element 102.2**, wherein, for example, the **first 126.1 and second 126.2 locations** on the **first patch antenna element 102.1** are substantially orthogonal with respect to one another, as are the corresponding **first 130.1 and second 130.2 locations** on the **second patch antenna element 102.2**. The **first 128.1 and second 128.2 delay lines** are interconnected with a **first conductive via 132.1** that extends through associated **first 134.1 and second 134.2 dielectric substrates** and through a **conductive ground plane 136** located therebetween. Similarly, the **third 128.3 and fourth 128.4 delay**

lines are interconnected with a **second conductive via 132.2** that also extends through the associated **first 134.1 and second 134.2 dielectric substrates** and through the **conductive ground plane 136**. In the embodiment illustrated in **FIG. 19**, the **first location 126.1** on the **first patch antenna element 102.1** is shown substantially orthogonal to the **first location 130.1** on the **second patch antenna element 102.2** so that the polarization of the radiation from the **second patch antenna element 102.2** is orthogonal with respect to that of the radiation incident upon the **first patch antenna element 102.1**. However, it should be understood that the **first locations 126.1 and 130.1** could be aligned with one another, or could be oriented at some other angle with respect to one another.

Referring to **FIGS. 20 and 21**, in accordance with a third embodiment of a **lens element 110^{III}** of the **planar lens 100.1**, one or more **delay lines 114** may be located between the **first 102.1 and second 102.2 patch antenna elements** -- rather than adjacent thereto as in the first and second embodiments of the **lens element 110^I, 110^{II}** -- so that the **delay lines 114** are shadowed by the associated **first 102.1 and second 102.2 patch antenna elements**. For example, in one embodiment, the **first patch antenna element 102.1** on a **first side 136.1** of a **first dielectric substrate 136** is connected with a **first conductive via 138.1** through the **first dielectric substrate 136** to a **first end 140.1** of a **first delay line 140** located between the **second side 136.2** of the **first dielectric substrate 136** and a **first side 142.1** of a **second dielectric substrate 142**. Similarly, the **second patch antenna element 102.2** on a **first side 144.1** of a **third dielectric substrate 144** is connected with a **second conductive via 138.2** through the **third dielectric substrate 144** to a **first end 146.1** of a **second delay line 146** located between the **second side 144.2** of the **third dielectric substrate 144** and a **first side 148.1** of a **fourth dielectric substrate 148**. A **third conductive via 138.3** interconnects the **second ends 140.2, 146.2** of the **first 140 and second 146 delay lines**, and extends through the **second 142 and fourth 148 dielectric substrates**, and through a **conductive ground plane 150** located between the **second sides 142.2, 148.2** of the **second 142 and fourth 148 dielectric substrates**. The **first 140 and second 146 delay lines** are shadowed by the **first 102.1 and second 102.2 patch antenna elements**, and therefore do not substantially affect the respective radiation patterns of the **first 102.1 and second 102.2 patch antenna elements**.

Referring to **FIG. 22**, in accordance with a second embodiment of a **planar lens 100.2**, the **patch antennas 102** are hexagonally shaped so as to provide for a more densely packed **discrete lens array 100'**. The particular shape of the individual **patch antennas 102**

is not limiting, and for example, can be circular, rectangular, square, triangular, pentagonal, hexagonal, or some other polygonal shape or an arbitrary shape.

Notwithstanding that **FIGS. 13, 15a, 15b, and 17-21** illustrate a plurality of delay lines **114.1, 114.2, 128.1, 128.2, 128.3, 128.4, 140, 146** interconnecting the **first 102.1 and second 102.2 patch antenna elements**, it should be understood that a **single delay line 114** - e.g. located on a surface of one of the **dielectric substrates 112, 134, 136, 142, 144** -- could be used, interconnected to the **first 102.1 and second 102.2 patch antenna elements** with associated conductive paths.

Referring to **FIGS. 23, 24a and 24b**, in accordance with a fourth embodiment of a lens element **110^{IV}** of the **planar lens 100.1**, the **first 102.1 and second 102.2 patch antenna elements** are interconnected with a **delay line 152** located therebetween, wherein a **first end 152.1** of the **delay line 152** is connected with a **first conductive via 154.1** to the **first patch antenna element 102.1** and a **second end 152.2** of the **delay line 152** is connected with a **second conductive via 154.2** to the **second patch antenna element 102.2**.

Referring to **FIG. 24a**, in accordance with a third embodiment of a **planar lens 100.3** incorporating the fourth embodiment of the **lens element 110^{IV}**, the **first patch antenna element 102.1** is located on a **first side 156.1** of a **first dielectric substrate 156**, and the **second patch antenna element 102.2** is located on a **first side 158.1** of a **second dielectric substrate 158**. The **delay line 152** is located between the **second side 156.2** of the **first dielectric substrate 156** and a **first side 160.1** of a **third dielectric substrate 160** and the **first conductive via 154.1** extends through the **first dielectric substrate 156**. A **conductive ground plane 162** is located between the **second sides 158.2, 160.2** of the **second 158 and third 160 dielectric substrates**, respectively, and the **second conductive via 154.2** extends through the **second 158 and third 160 dielectric substrates** and through the **conductive ground plane 162**. Referring to **FIG. 24b**, a fourth embodiment of a **planar lens 100.4** incorporates the fourth embodiment of a **lens element 110^{IV}** illustrated in **FIG. 23**, without the **third dielectric substrate 160** of the third embodiment of the **planar lens 100.3** illustrated in **FIG. 24a**, wherein the **delay line 152** and the **conductive ground plane 162** are coplanar between the **second sides 156.2, 158.2** of the **first 156 and second 158 dielectric substrates**, and are insulated or separated from one another.

The **discrete lens array 100** does not necessarily have to incorporate a **conductive ground plane 122, 136, 150, 162**. For example, in the fourth embodiment of a **planar lens 100.4** illustrated in **FIG. 24b**, the **conductive ground plane 162** is optional, particularly if a

closely packed array of **patch antennas 102** were used as illustrated in **FIG. 22**. Furthermore, the first embodiment of a **lens element 110^I** illustrated in **FIG. 18** could be constructed with the **first 102.1 and second 102.2 patch antenna elements** on opposing sides of a single **dielectric substrate 112**.

5 Referring to **FIGS. 25 and 26**, in accordance with the third aspect and a seventh embodiment of a **multi-beam antenna 10^{II}**, **10.7**, and a fifth embodiment of a **lens element 110^V** illustrated in **FIG. 26**, a **reflective discrete lens array 164** comprises a plurality of **patch antennas 102** located on a **first side 166.1** of a **dielectric substrate 166** and connected via corresponding **delay lines 168** that are terminated either with an open or short
10 circuit, e.g. by termination at an associated **conductive ground plane 170** on the **second side 166.2** of the **dielectric substrate 166**, wherein the associated delays of the **delay lines 168** are adapted -- for example, as illustrated in **FIG. 16** -- so as to provide a phase profile that emulates a dielectric lens, e.g. a dielectric **electromagnetic lens 12^{III}** as illustrated in **FIG. 10**. Accordingly, the **reflective discrete lens array 164** acts as a reflector and provides for
15 receiving electromagnetic energy in the associated **patch antennas 102**, and then reradiating the electromagnetic energy from the **patch antennas 102** after an associated location dependent delay, so as to provide for focusing the reradiated electromagnetic energy in a desired direction responsive to the synthetic structure formed by the phase front of the reradiated electromagnetic energy responsive to the location dependent delay lines.

20 In the sixth embodiment of the **multi-beam antenna 10.6** illustrated in **FIG. 12**, and a seventh embodiment of a **multi-beam antenna 10.7** illustrated in **FIG. 26**, which correspond in operation to the first and fourth embodiments of the **multi-beam antenna 10.1, 10.4** illustrated in **FIGS. 1 and 10** respectively, the **discrete lens array 100, 164** is adapted to cooperate with a plurality of **antenna feed elements 14**, e.g. **end-fire antenna element**
25 **14.1** located along the edge of a **dielectric substrate 16** having an **edge contour 30** adapted to cooperate with the focal surface of the associated **discrete lens array 100, 164**, wherein the **antenna feed elements 14** are fed with a **feed signal 28** coupled thereto through an associated **switching network 48**, whereby one or a combination of **antenna feed elements 14** may be fed so as to provide for one or more **beams of electromagnetic energy 20**, the
30 direction of which can be controlled responsive to a **control signal 60** applied to the **switching network 48**.

Referring **FIG. 27**, in accordance with the fourth aspect and an eighth embodiment of a **multi-beam antenna 10^{III}**, **10.8**, which corresponds in operation to the fifth embodiment of

the **multi-beam antenna 10.5** illustrated in **FIG. 11**, the **discrete lens array 100** can be adapted to cooperate with a plurality of **dielectric substrates 16**, each comprising a set of **antenna feed elements 14** and operating in accordance with the description hereinabove. Each set of **antenna feed elements 14** generates or receives (or is capable of generating or receiving) an associated set of **beams of electromagnetic energy 20.1, 20.2 and 20.3**, each having associated **directions 42.1, 42.2 and 42.3**, responsive to the associated **feed 58 and control 60 signals**. The associated **feed 58 and control 60 signals** are either directly applied to the associated **switch network 48** of the respective sets of **antenna feed elements 14**, or are applied thereto through a **second switch network 78** have associated **feed 80 and control 82 ports**, each comprising at least one associated signal. Accordingly, the **multi-beam antenna 10.8** provides for transmitting or receiving one or more beams of electromagnetic energy over a three-dimensional space.

Generally, because of reciprocity, any of the above-described antenna embodiments can be used for either transmission or reception or both transmission and reception of electromagnetic energy.

The **discrete lens array 100, 164** in combination with planar, **end-fire antenna elements 14.1** etched on a **dielectric substrate 16** provides for a **multi-beam antenna 10** that can be manufactured using planar construction techniques, wherein the associated **antenna feed elements 14** and the associated **lens elements 110** are respectively economically fabricated and mounted as respective groups, so as to provide for an antenna system that is relatively small and relatively light weight.

While specific embodiments have been described in detail in the foregoing detailed description and illustrated in the accompanying drawings, those with ordinary skill in the art will appreciate that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure. Accordingly, the particular arrangements disclosed are meant to be illustrative only and not limiting as to the scope of the invention, which is to be given the full breadth of the appended claims, and any and all equivalents thereof.

What is claimed is:

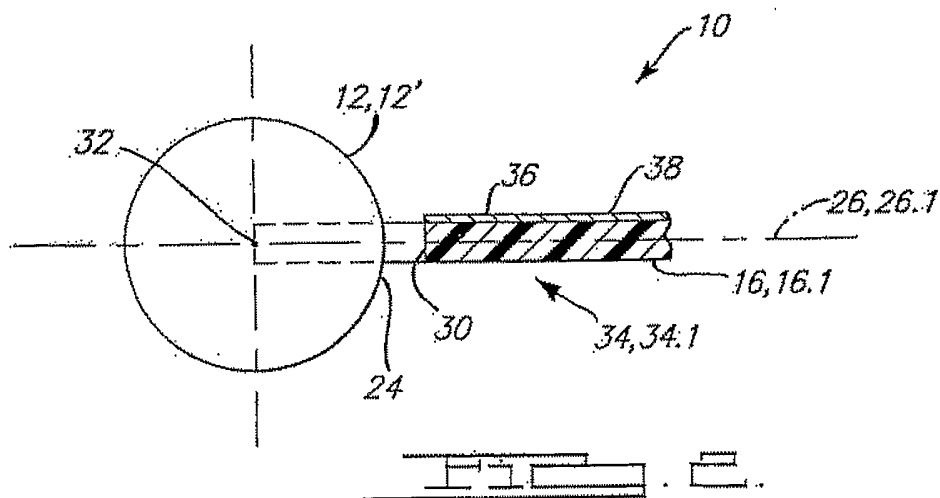
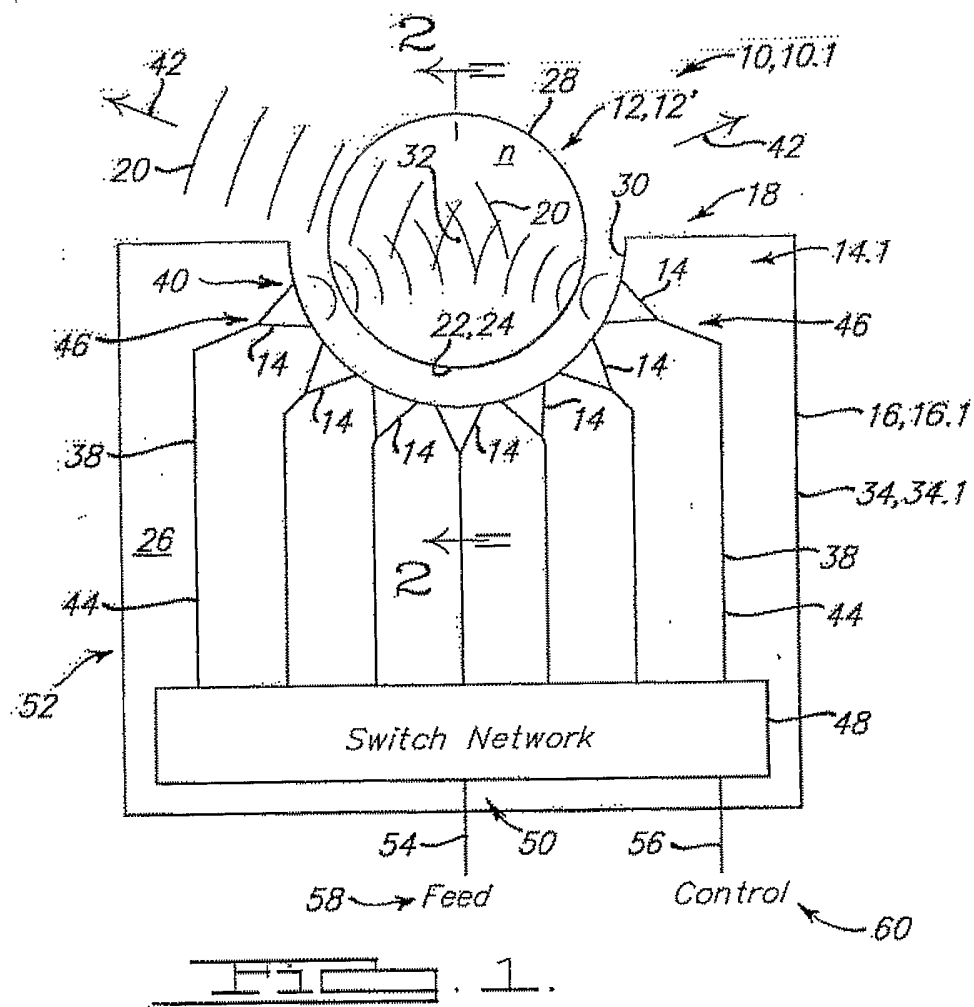
CLAIMS

1. A multi-beam antenna, comprising:

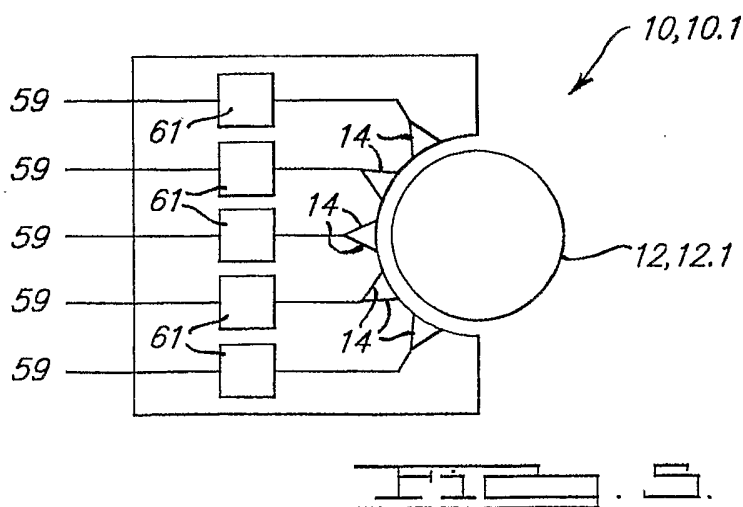
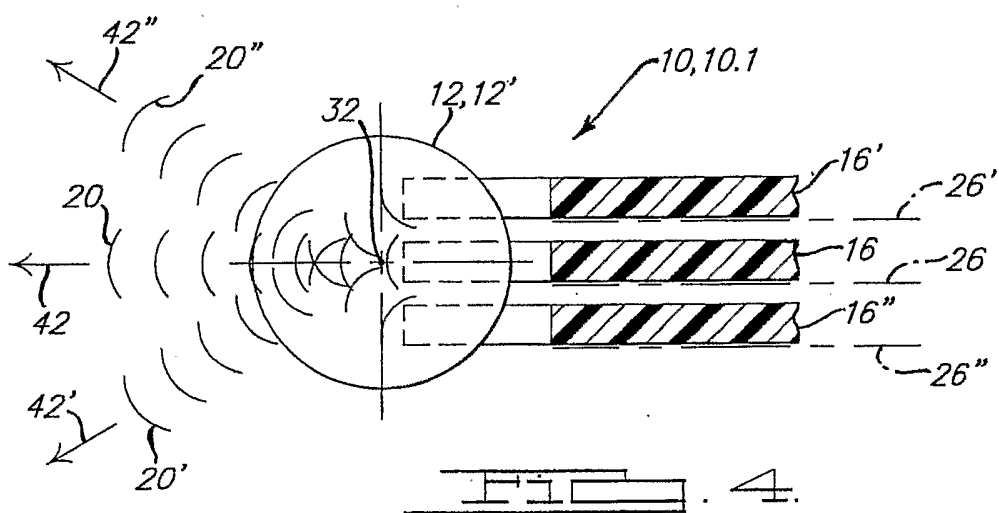
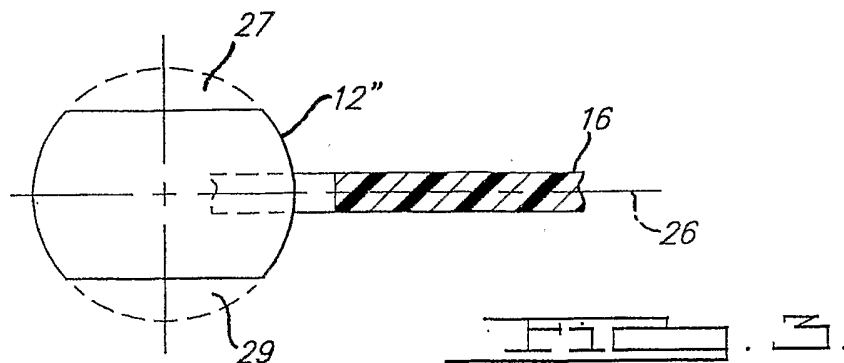
- a. an electromagnetic lens, wherein said electromagnetic lens comprises a nominal focal surface, and said nominal focal surface is curved;
- 5 b. a dielectric substrate in a cooperative relationship with said electromagnetic lens; and
- c. a plurality of antenna feed elements on said dielectric substrate at a corresponding plurality of locations and oriented in a corresponding plurality of directions, wherein a least two of said plurality of antenna elements are located at a corresponding at least two different locations, said at least two of said plurality of antenna elements are each adapted act along a corresponding at least two different directions, and said at least two different directions and said at least two different locations are adapted in relation to said nominal focal surface of said electromagnetic lens so as to provide for at least one of transmitting and receiving a plurality of different electromagnetic beams in or from a plurality of different said directions in cooperation with said electromagnetic lens.

- 2.** A multi-beam antenna as recited in claim **1**, wherein said electromagnetic lens comprises a plurality of lens elements in a discrete lens array, wherein each said lens element comprises first and second patch elements; at least one dielectric layer interposed between said first and second patch elements, wherein said first patch element is located on a first surface of said at least one dielectric layer, and said second patch element is located on a second surface of said at least one dielectric layer; and at least one delay element operative between said first and second patch elements; wherein said first and second patch elements are located on respective first and second sides of said electromagnetic lens, said first side of said electromagnetic lens is adapted to be in electromagnetic wave communication with said plurality of antenna feed elements, said at least one delay element operative between said first and second patch elements delays a propagation of an electromagnetic wave between said first and second patch elements by a delay period, and said delay period of at least one of said electromagnetic lens elements is different from a delay period of at least another of said electromagnetic lens elements.

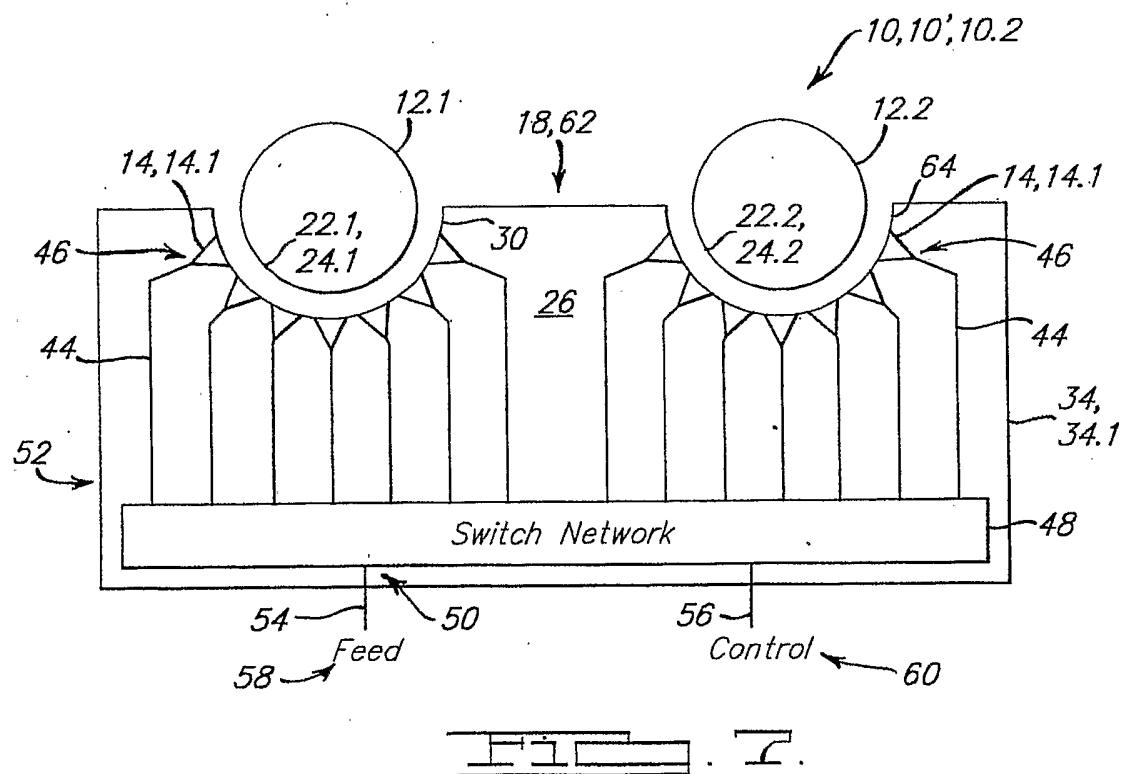
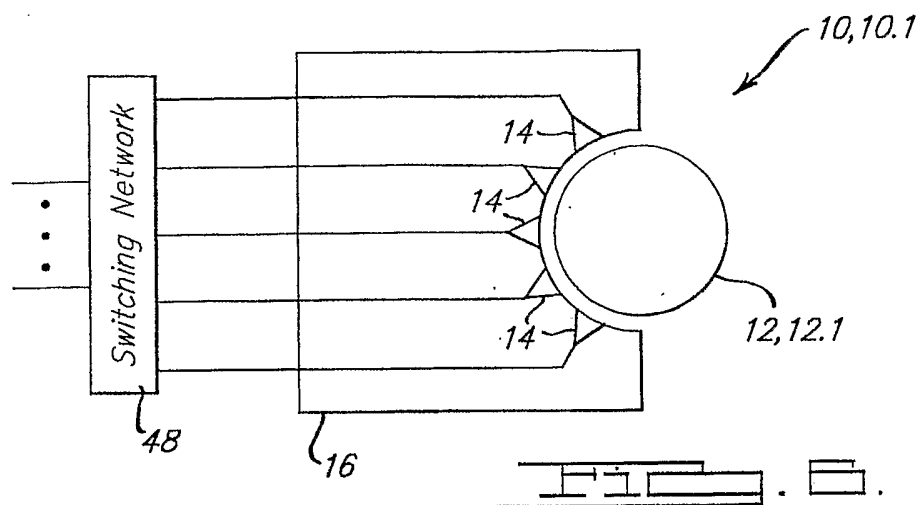
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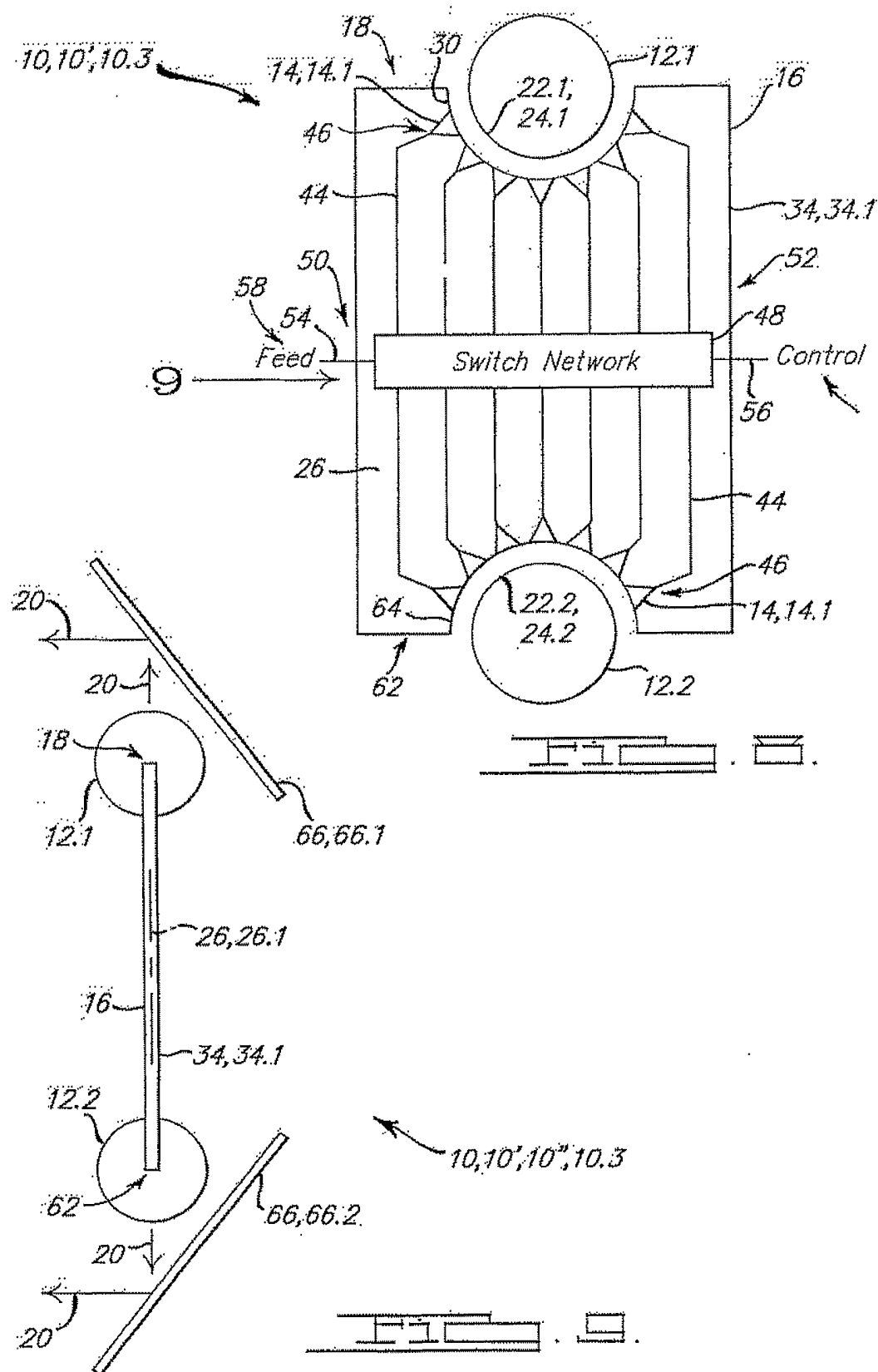


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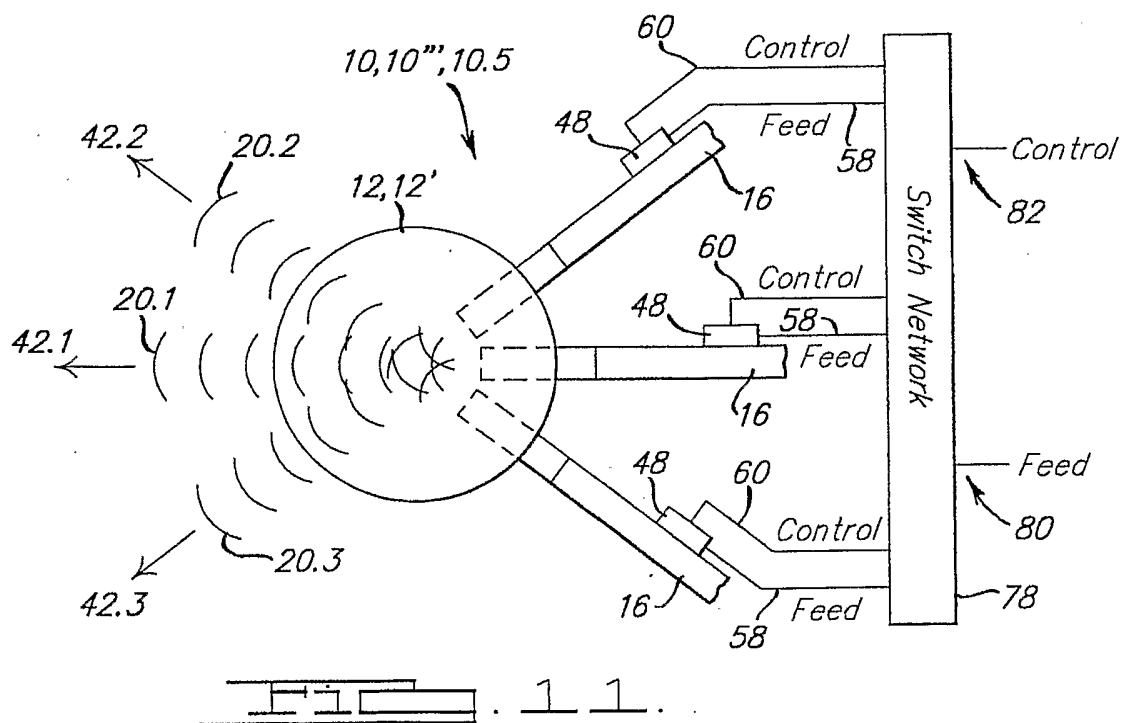
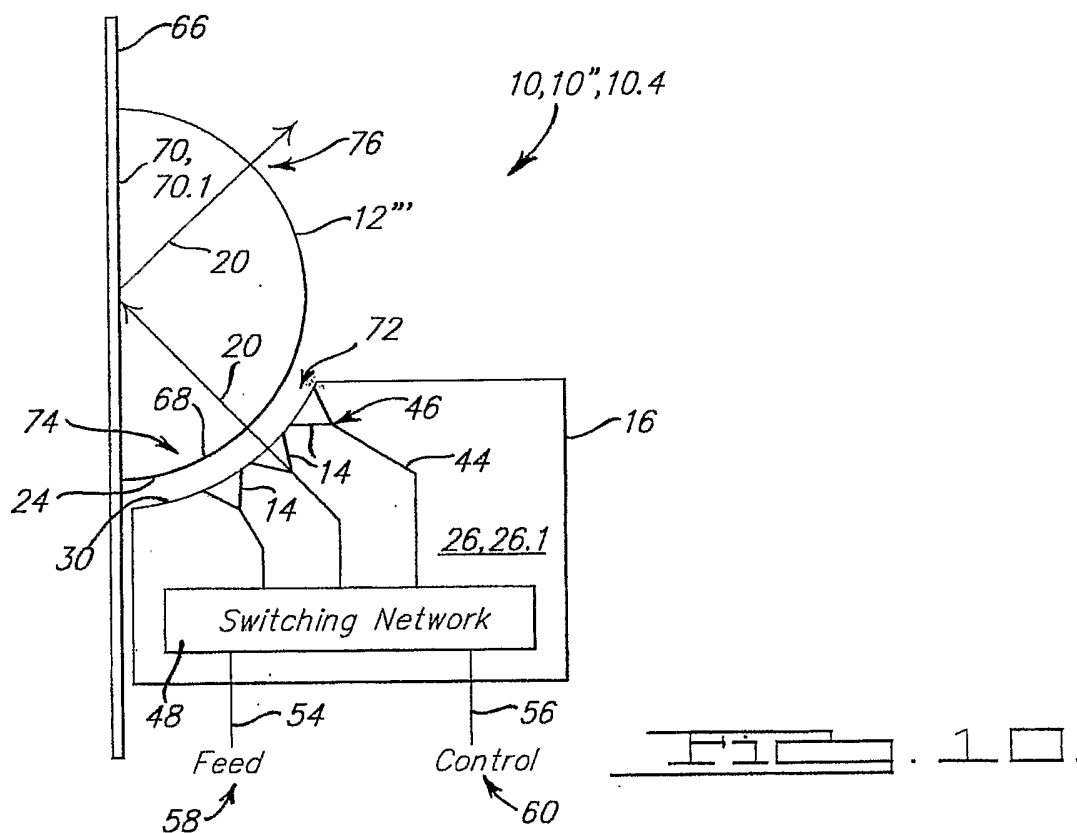


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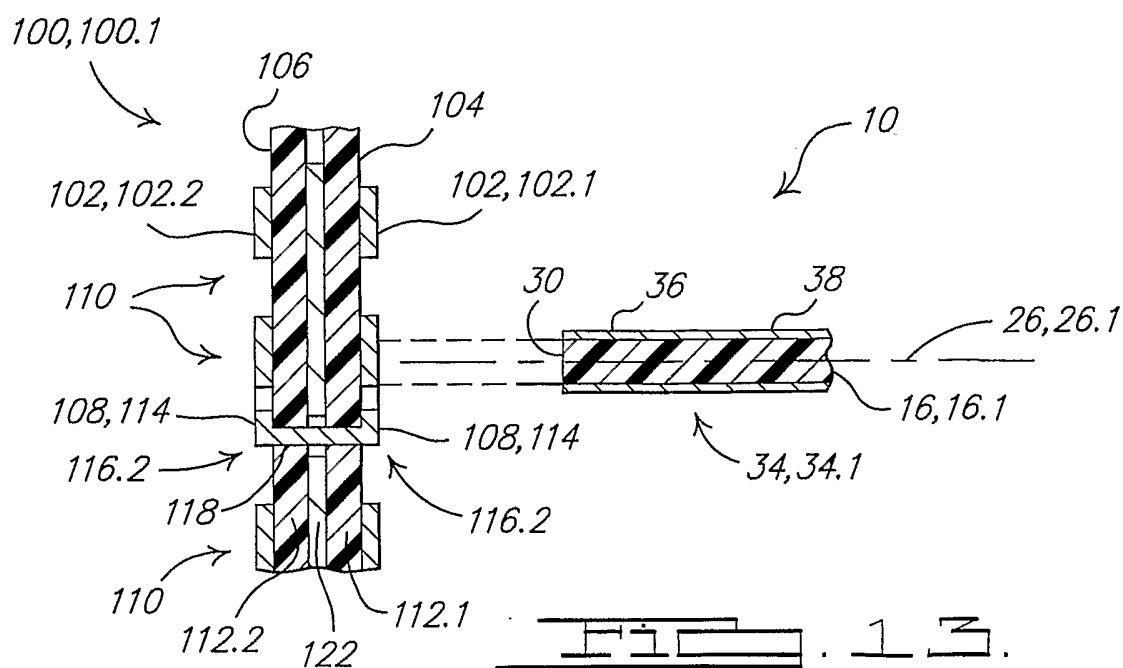
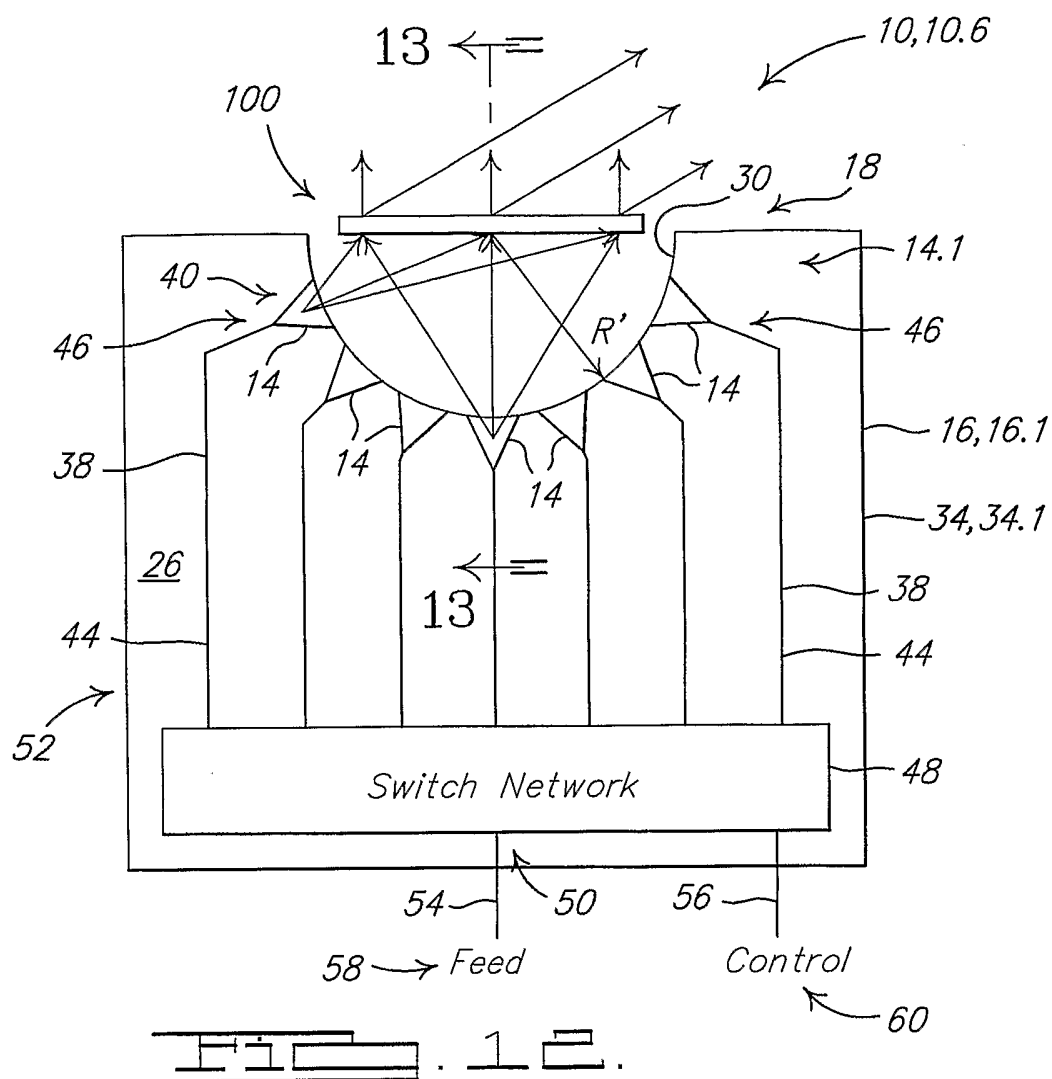




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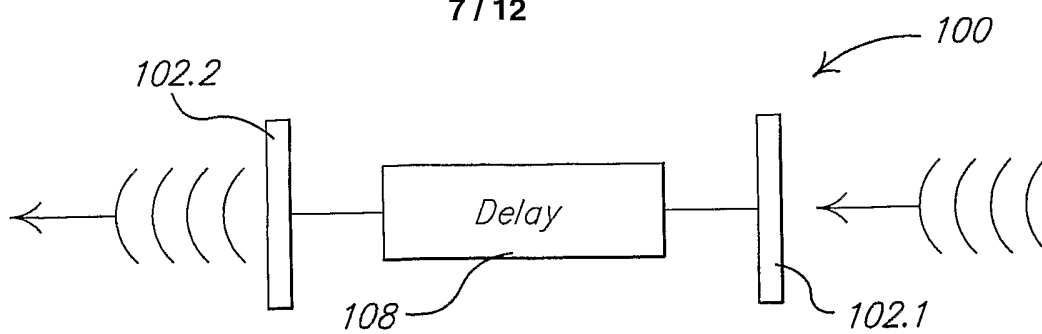


FIG. 14.

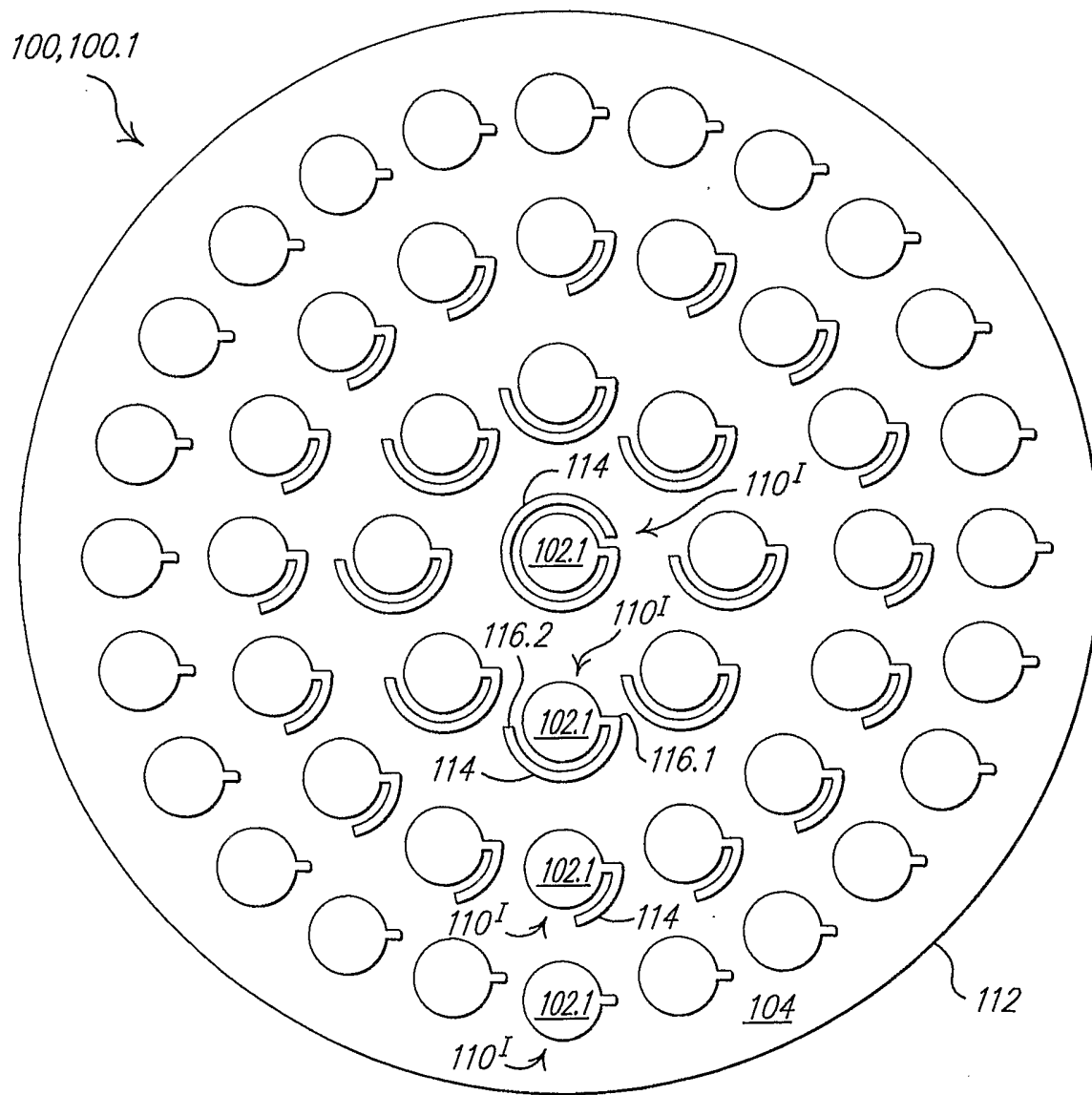


FIG. 15a.

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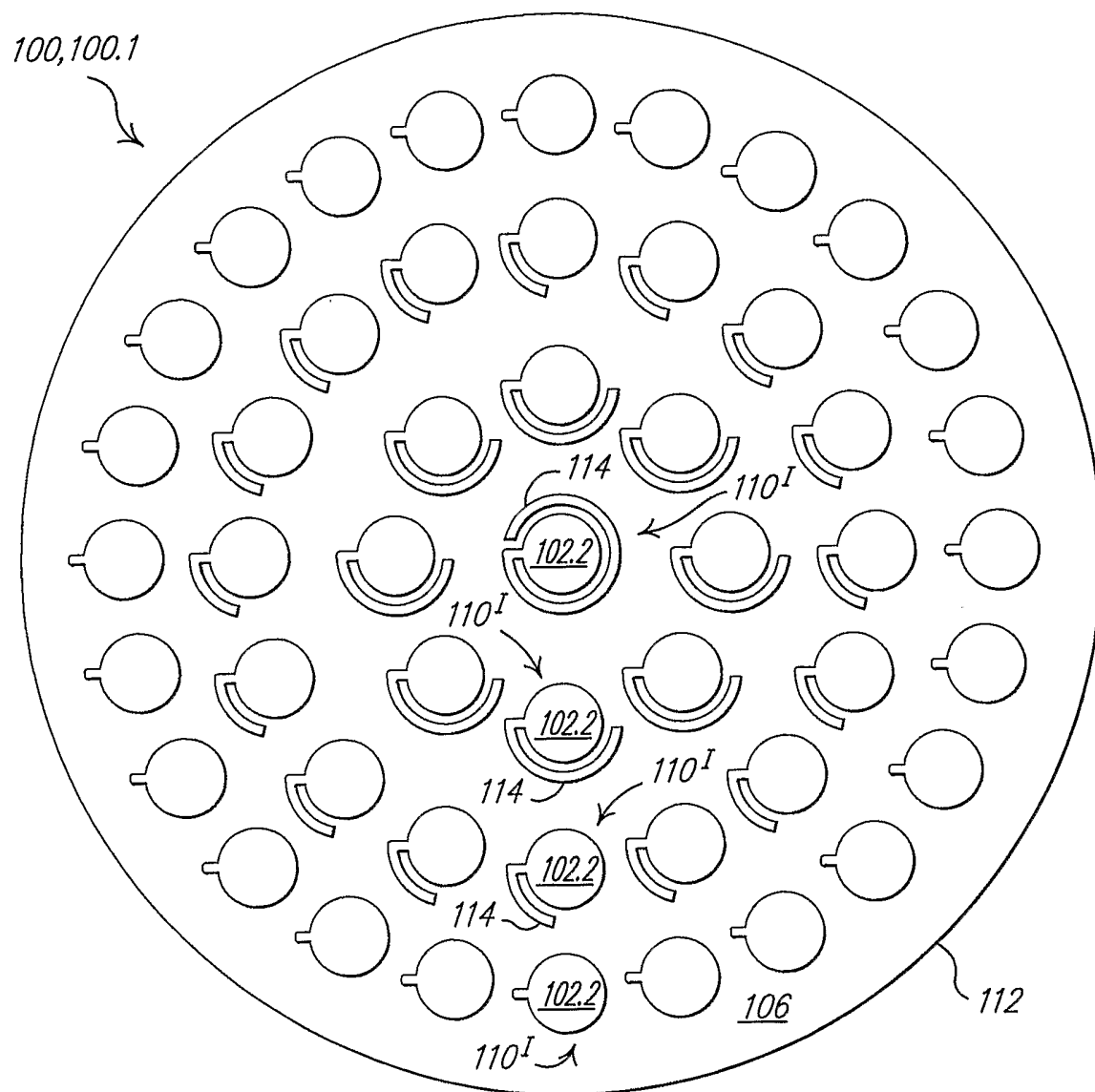


FIG. 15b.

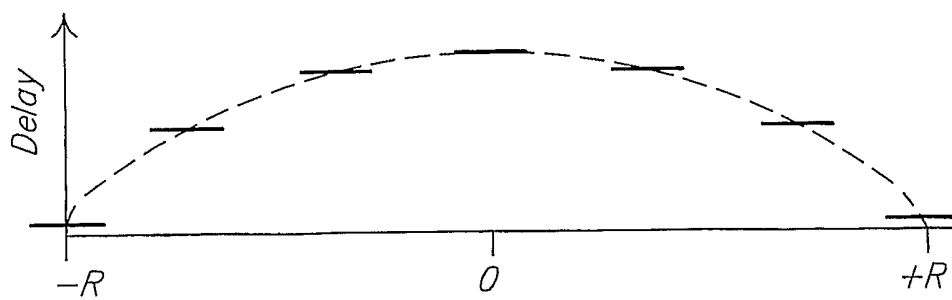
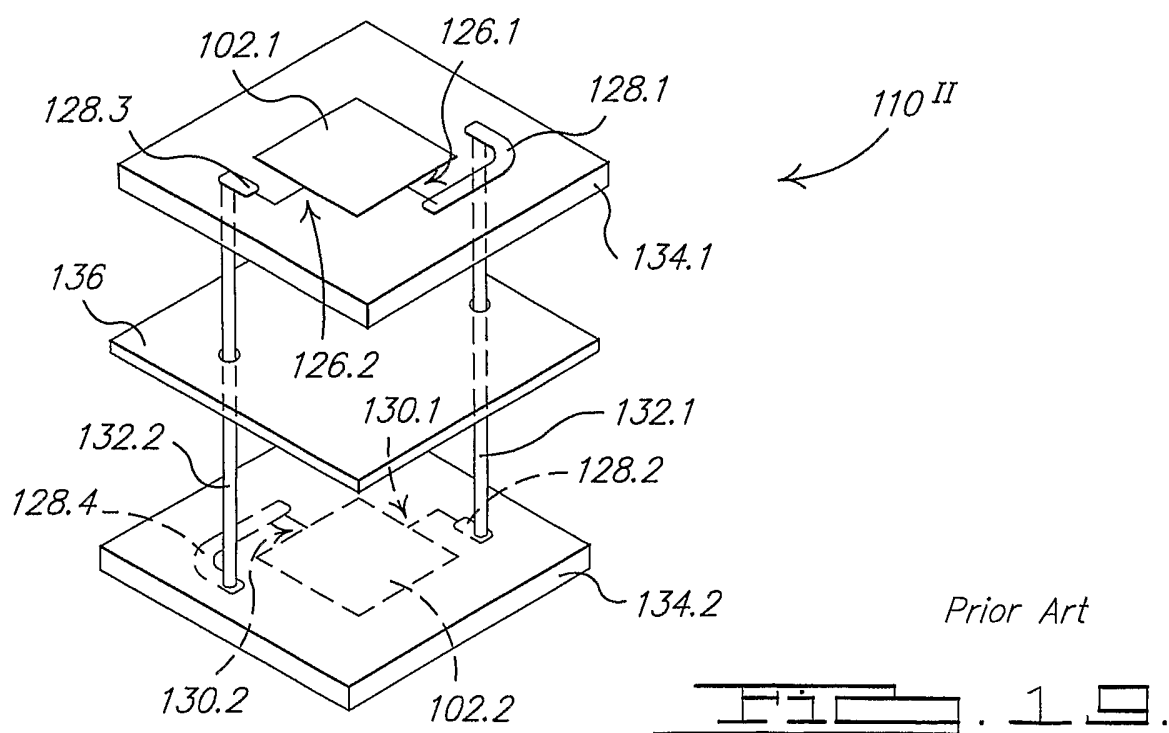
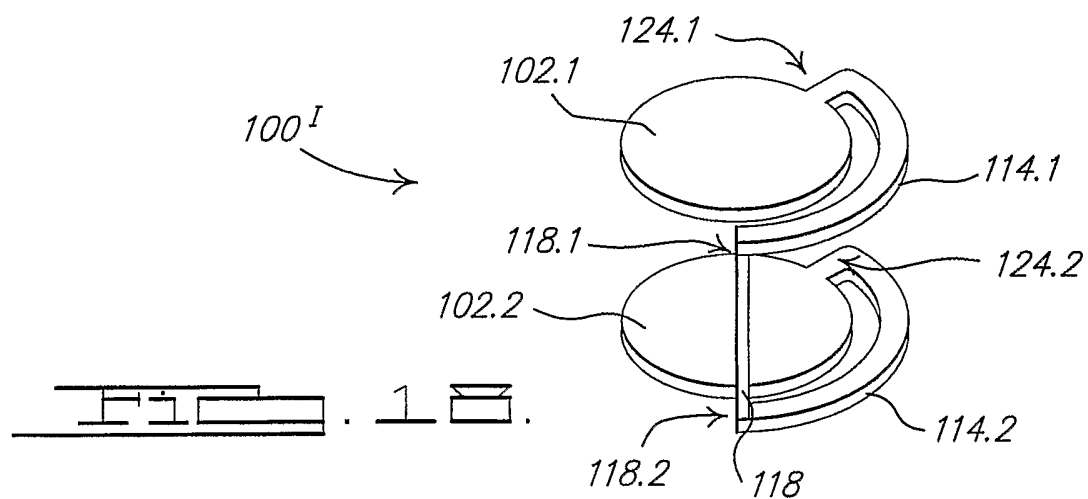
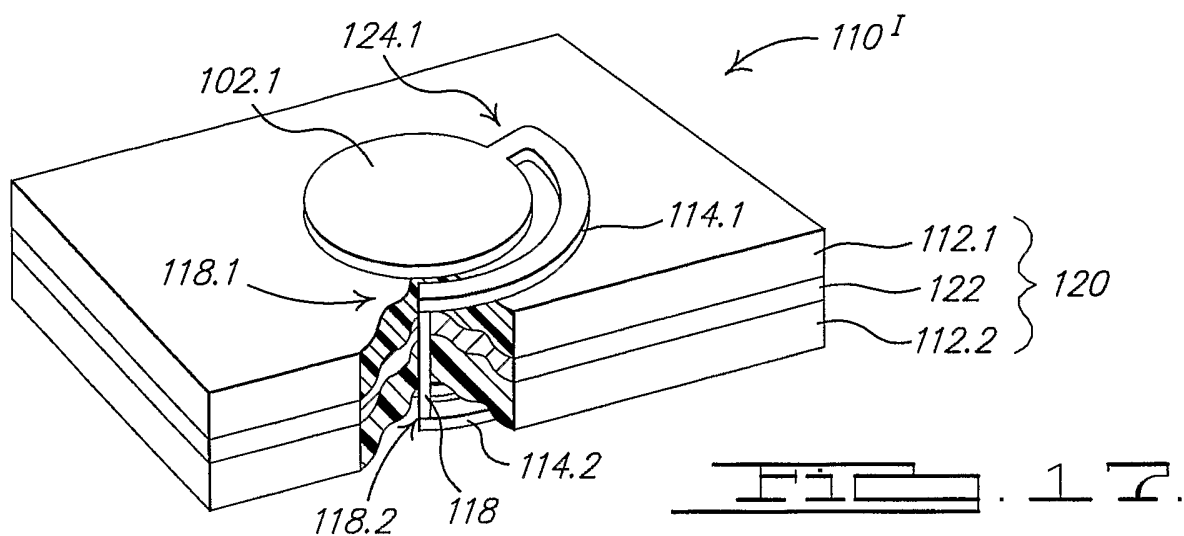
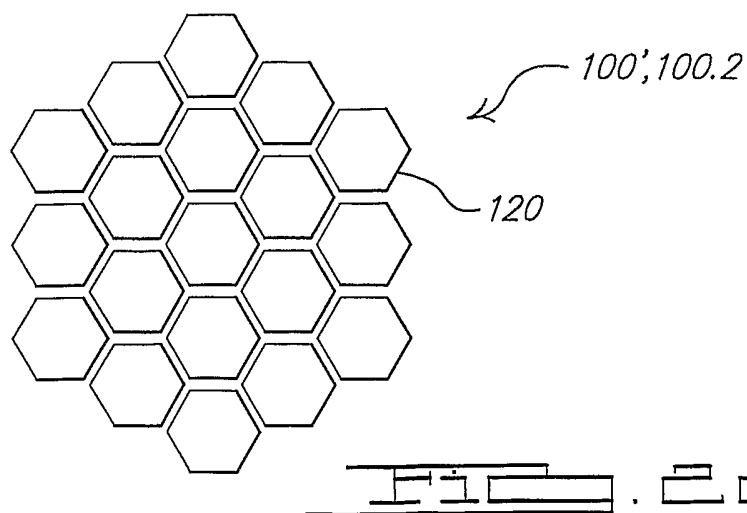
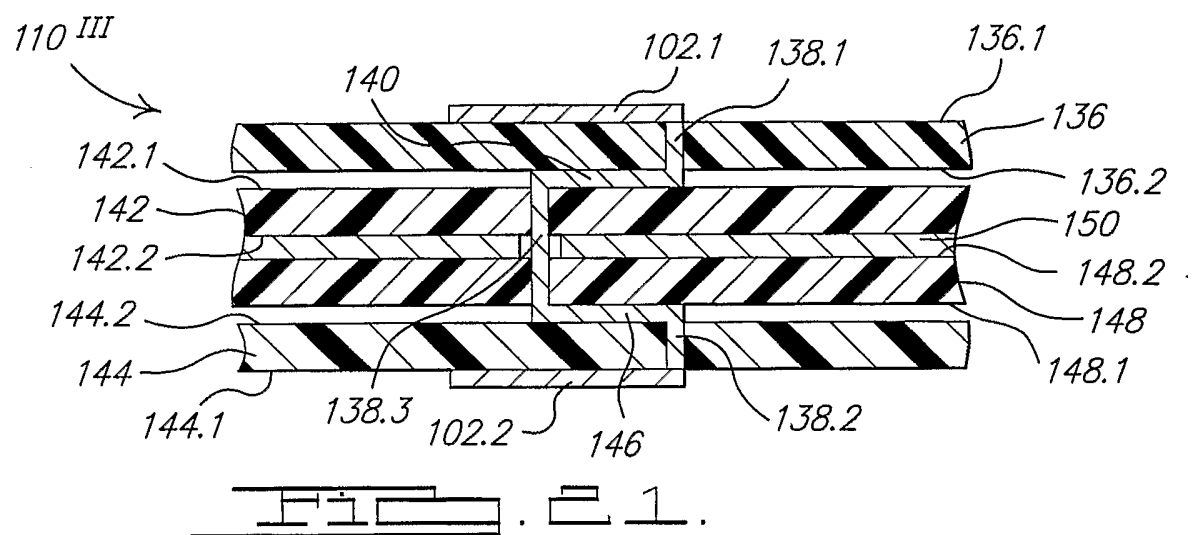
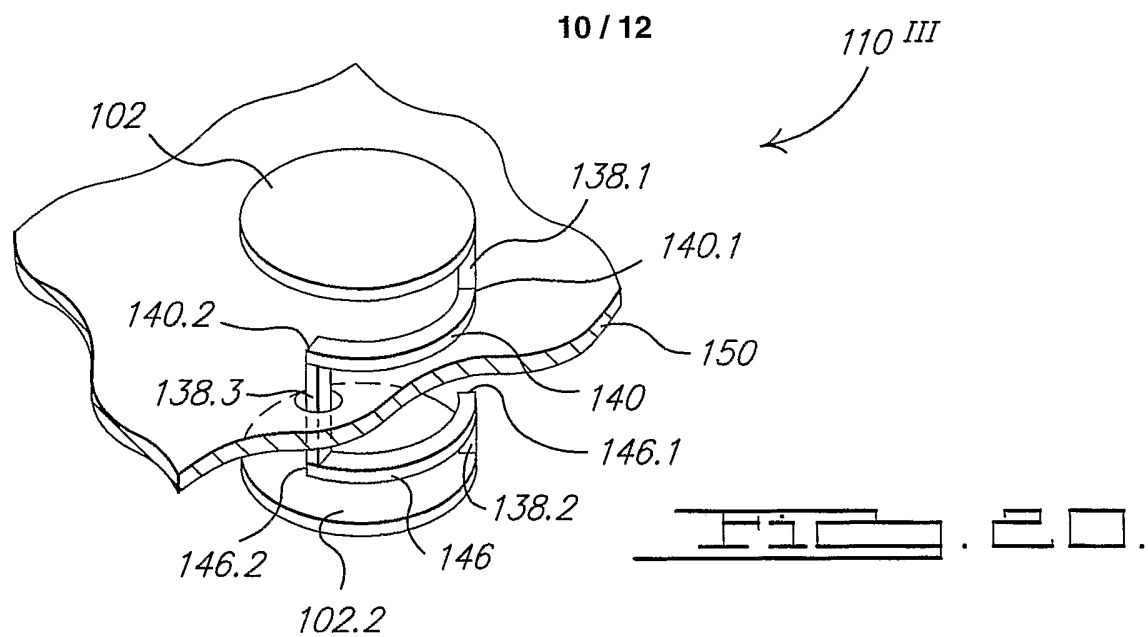


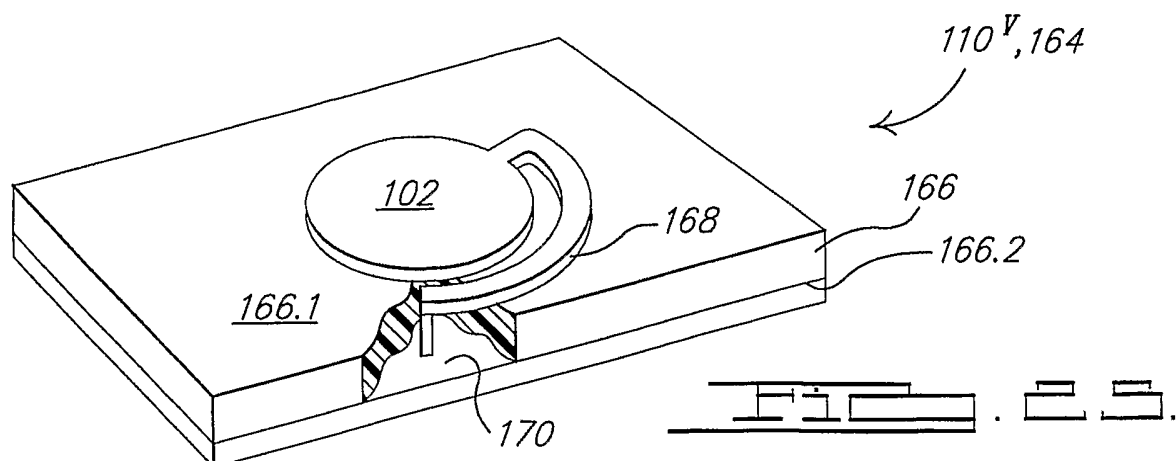
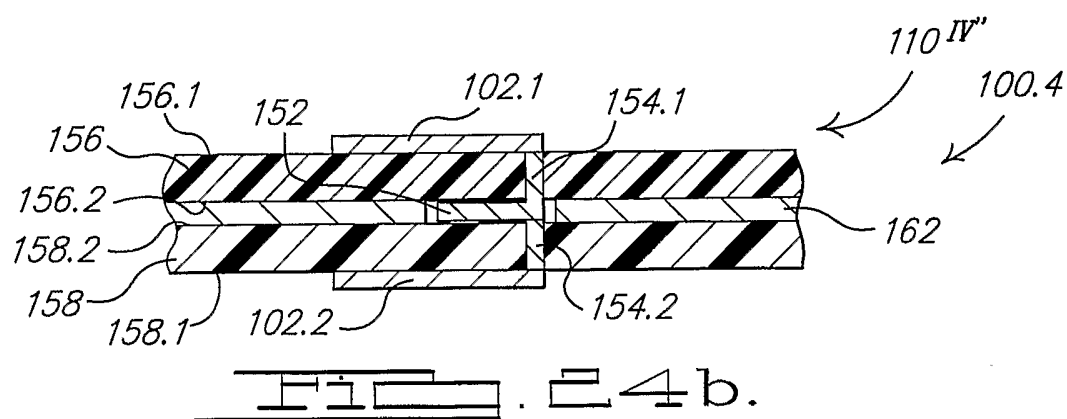
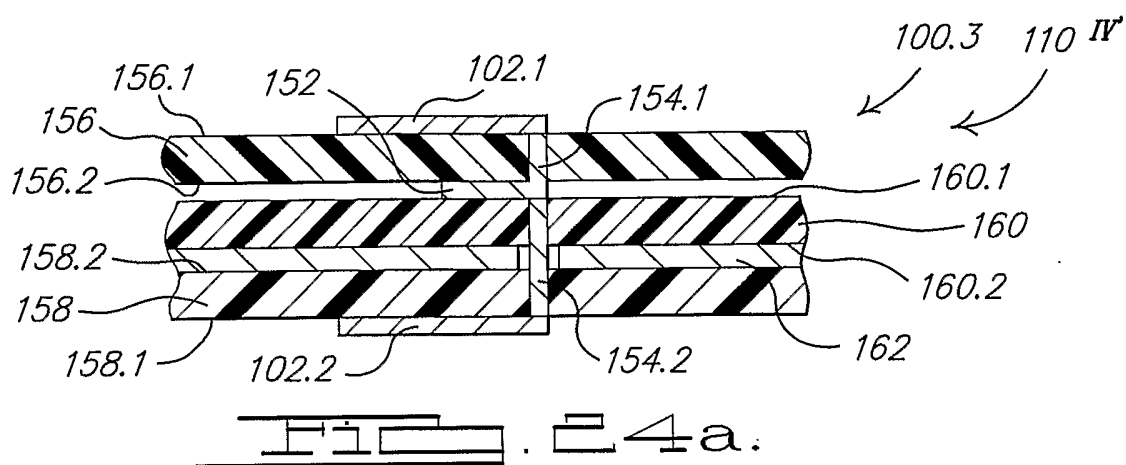
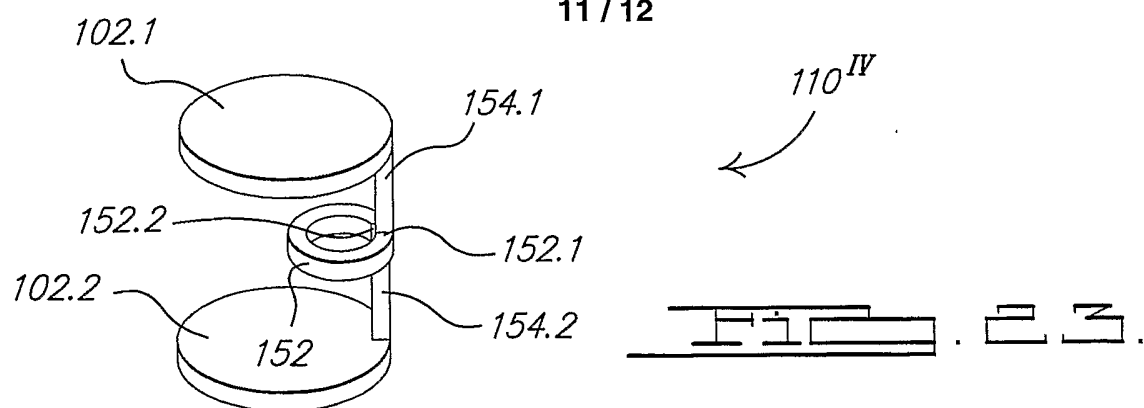
FIG. 16.

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