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(71) Applicant (*for all designated States except US*): RAMBUS INC. [US/US]; 4440 El Camino Real, Los Altos, CA 94022 (US).

(72) Inventors; and

(75) Inventors/Applicants (*for US only*): WERNER, Carl, W. [US/US]; 124 Briarwood Way, Los Gatos, CA 95032 (US). FRANCA-NETO, Luiz, M. [BR/US]; 1252 Gainsborough Drive, Sunnyvale, CA 94087 (US).

(74) Agent: BEHIEL, Arthur, J.; Silicon Edge Law Group LLP, 6601 Koll Center Parkway, Suite 245, Pleasanton, CA 94566 (US).

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(54) **Title:** RADIO BEAM FORMING ANTENNA WITH ELECTROACTIVE POLYMER ACTUATOR

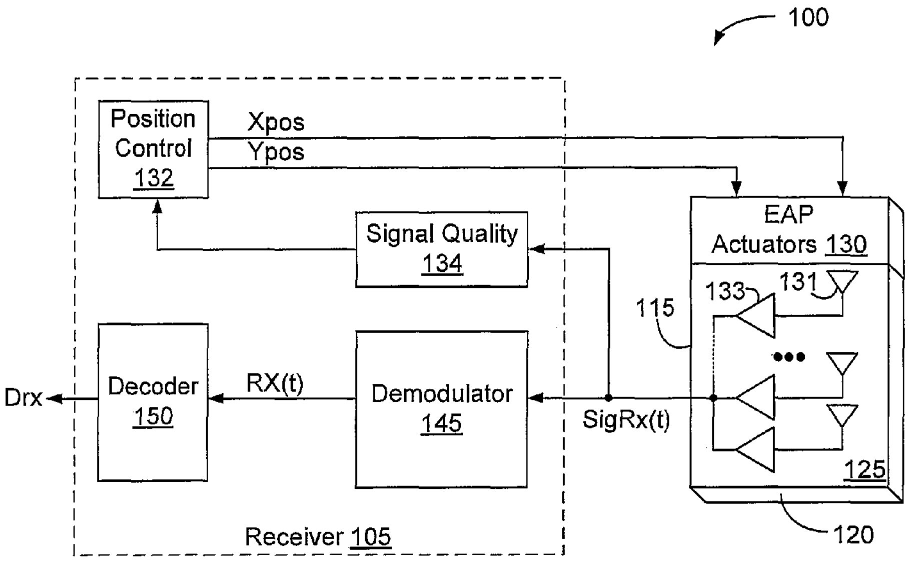

Fig. 1

(57) **Abstract:** A millimeter-wave radio employs directional antennal arrays, electroactive polymer actuators, and associated control circuitry to direct millimeter-wave radio signals. The directionality provides antenna gain that addresses the attenuation problems associated with millimeter waves, while the directional control and power efficiency of the electroactive polymer actuators supports flexible radio placement.

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RADIO BEAM FORMING ANTENNA WITH ELECTROACTIVE POLYMER ACTUATOR

Carl W. Werner

Luiz M. Franca-Neto

TECHNICAL FIELD

[0001] The subject matter disclosed herein relates generally to the field of communications, and more particularly to millimeter-wave radios.

BACKGROUND

[0002] Millimeter-wave radios, which employ modulation frequencies in the forty to one hundred twenty gigahertz range, have potential to transmit data in the range of one to ten gigabits per second. Unfortunately, millimeter waves are highly sensitive to atmospheric attenuation. In particular, sixty gigahertz radio signals suffer severe losses due to interaction with oxygen. On the plus side, Federal Communications Commission (FCC), the government agency responsible for regulating use of the radio spectrum, does not require a license for low-power, sixty-gigahertz radio signals. Further, the relatively short wavelengths of millimeter-wave radios allow for relatively small and directional antenna configurations that can be used for point-to-point applications.

[0003] As of this writing, the sixty gigahertz band is essentially undeveloped. What is needed are systems that overcome the attenuation problems associated with millimeter waves to take advantage of the available spectrum.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] The subject matter disclosed is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements and in which:

[0005] Figure 1 illustrates a millimeter-wave radio 100 that employs directional antennal arrays, electroactive polymer actuators, and associated control circuitry to direct millimeter-wave radio signals.

[0006] Figure 2 depicts antenna system 115 of Figure 1 in accordance with one embodiment.

[0007] Figures 3A and 3B depict a radio 300 like radio 100 of Figure 1, with like-identified elements being the same or similar.

[0008] Figure 4 depicts a communication system 400 that illustrates the operation of a communicating pair of radios 405 and 410 in accordance with one embodiment.

[0009] Figure 5 depicts millimeter-wave radio 405 of Figure 4 in accordance with one embodiment.

[0010] Figure 6 is a state diagram 600 detailing the operation of position control circuitry 570 of Figure 5 in accordance with an embodiment that identifies alternative signal paths and automatically selects from among them to maintain signal integrity.

[0011] Figure 7 depicts a radio 700 in accordance with one embodiment that combines phase offsets with physical displacement for directional control of a receive antenna array 705 configured to receive a circularly polarized millimeter-wave radio signal.

DETAILED DESCRIPTION

[0012] Figure 1 illustrates a millimeter-wave radio 100 that employs a directional antennal array, electroactive polymer (EAP) actuators, and associated control circuitry to direct millimeter-wave radio signals. The directionality provides antenna gain that addresses the attenuation problems associated with millimeter waves, while the directional control and power efficiency of the EAP actuators supports flexible radio placement.

[0013] Radio 100 includes a receiver 105 and an actuated receive antenna system 115. Antenna system 115 in turn includes a support 120 supporting an antenna array 125 and EAP actuators 130 that move array 125 relative to support 120. Antenna array 125 includes an array of antennas 131 and associated amplifiers 133. Antenna arrays 110 and 125 each communicate millimeter-wave signals with frequencies of between forty and one hundred twenty gigahertz.

[0014] Receiver 105 includes position control circuitry 132 and a signal-quality monitor 134 that together control the direction of antenna array 125 by application of analog position-control signals Xpos and Ypos to actuators 130. Receiver 105 additionally includes a demodulator 145 that demodulates a receive signal SigRx(t) from antenna system 115 to produce a receive signal RX(t). A decoder 150 decodes signal RX(t) to recover receive data Drx.

[0015] Actuators 130 are sandwich structures in which an elastomeric material disposed between conductive layers deforms in response to voltage applied between the conductive layers. These actuators behave like capacitors under excitation voltages and provide considerable deflection with little steady-state power consumption. For a suitable EAP actuator, see Bonwit et al. “Design of Commercial Applications of EPAM Technology” (2006). That reference describes a linear actuator offered by Artificial Muscle, Inc., of Menlo Park, California.

[0016] Figure 2 depicts antenna system 115 of Figure 1 in accordance with one embodiment. For brevity, Figure 2 omits all but one each of antennas 131 and amplifiers 133. In this embodiment, antenna 131 is a dipole antenna that includes two orthogonal pairs of antenna halves 200 and 205 that are designed to receive a circularly polarized millimeter-wave signal. Amplifier 133 includes a pair of differential amplifiers 210 and 215 and a phase shifter 220. The differential input terminals of amplifier 210 are coupled to respective ones of antenna halves 200, while the differential input terminals of amplifier 215 are coupled to respective ones of antenna halves 205. The output from amplifier 215 is coupled directly to node SigRx(t); the output from amplifier 210 is coupled to node SigRx(t) via phase shifter

220, which offsets the signal received on antenna halves 200 by $\pi/2$ radians (90 degrees) before applying the resulting inverted signal to node SigRx(t). Amplifier 133 is well understood by those of skill in the art, so a detailed discussion is omitted for brevity.

[0017] Figures 3A and 3B depict a radio 300 like radio 100 of Figure 1, with like-identified elements being the same or similar. Radio 300 omits the transmitting portion of radio 100, including antenna array 110, but this or similar components can be included in other embodiments.

[0018] Figure 3A is a plan view of radio 300. Receive antenna array 115 and amplifiers 133 are stacked printed-circuit (PC) boards, or stacked integrated circuit packages, electrically coupled by a number of vias 303. The PC boards are collectively coupled to support 120 via four actuators 130. Modem 105, though not shown here, may be incorporated into or attached to support 120 or integrated with amplifiers 133. However configured, modem 105 receives signals from antennas 125 and issues position-control signals to actuators 130. The position control signals Xpos and Ypos (Figure 1) selectively lengthen or shorten selected ones of actuators 130 along a direction normal to the page to direct antenna array 115. Antennas 125 of array 115 are arranged in a two-dimensional array in which the center-to-center spacing of the antennas is between about 0.7 and 0.9 times the wavelength, λ_{AIR} ,of the received beam propagating in air and the tips of the dipole halves are spaced by about half the wavelength, λ_{SUB} ,of the received beam propagating in the substrate upon which antenna halves 200 and 205 are formed. Dipole antennas of the type depicted are relatively simple to make, but other embodiments can use different types of antennas and antenna arrays.

[0019] Figure 3B depicts three side views of radio 300 showing the operation of actuators 130. Figure 3B also shows a cable 350 that communicates signal SigRx(t) from antenna array 125 to support 120. In the upper view, all of actuators 130 are of the same length, in which case the surface of antenna array 115 is parallel to the surface of support 120. In the middle view, the rightmost actuators 130 are shorter than the leftmost actuators 130, in which case the surface of antenna array 115 is tilted to the right with respect to support 120. In the bottom view, the front-side actuators 130 are shorter than the rearward actuators 130 (not shown). The lengths of actuators 130 can be varied continuously over range of lengths responsive to a range of applied voltages so the direction of antenna array 115 can be adjusted in two dimensions.

[0020] Figure 4 depicts a communication system 400 that illustrates the operation of a communicating pair of radios 405 and 410 in accordance with one embodiment. Prior embodiments included directional receive antenna arrays that could be adjusted over a range of angles. Transmit antennas can be similarly adjustable, and systems in accordance with various embodiments can include adjustable transmit antennas, receive antennas, or both. In the example of Figure 4, a video source 415 communicates a video signal to a wall-mounted video display 425. Radio 405 in video source 415 is adapted in accordance with one embodiment to direct a beam 430 to an omni-directional antenna (not shown) in radio 410. Display 425 can transmit information back to video source 415 using the same or a different communication scheme as used for beam 430. For example, display 425 and video source 415 can support a separate communication channel that supports relatively lower data rates to convey information unidirectionally or bidirectionally between display 425 and video source 415. In other embodiments one or both of radios 405 and 410 are instantiated on mobile devices, and the information conveyed is not limited to video data.

[0021] Beam 430 is directional to improve antenna gain, which is particularly important for millimeter-wave signals. Ideally, beam 430 is emitted directly at receiving radio 410 and reception is optimal. Such a direct transmission path may not be available, however, in which case system 400 may take advantage of one or more alternative paths. In this example, beam 430 can be directed to radio 410 via a path 450 that bounces off a neighboring wall or an alternative path 455 that bounces off the floor. Additional alternatives might also be available. Radios in accordance with some embodiments identify a plurality of alternative signal paths and automatically select from among them periodically or in response to degraded or lost signals. Such radios can adapt for changes in the communication environment. In the example of Figure 4, a viewer or a piece of furniture might block a selected path, in which case radio 405 can automatically select a suitable alternative path.

[0022] Figure 5 depicts millimeter-wave radio 405 of Figure 4 in accordance with another embodiment. Radio 405 includes a modem 500 coupled to an actuated, directional antenna system 505 that transmits and receives millimeter-wave radio signals. Antenna system 505 includes a substrate 510 supporting a receive antenna array 515 and a transmit antenna array 520, both of which may be moved relative to substrate 510 using a common set of EAP actuators 525.

[0023] Antenna array 515 includes an array of antennas 530 and associated amplifiers 535. Array 520 includes a similar array of antennas 540 coupled to the outputs of respective amplifiers 545. Both antenna arrays 515 and 520 may be of the type detailed above in connection with Figures 3A and 3B to communicate millimeter-wave signals with frequencies of between e.g. forty and ninety gigahertz.

[0024] On the transmit side, modem 500 includes an encoder 550 and modulator 555. Encoder 550 encodes a data signal Dtx to produce a continuous-time signal TX(t), which modulator 555 modulates to produce a millimeter-wave transmission signal SigTx(t). Antenna array 520 then creates and transmits beam 430 (Figure 4) from signal SigTx(t). On the receive side, modem 500 includes a demodulator 560 and associated decoder 565. Antenna array 515 recovers a millimeter-wave signal as received signal SigRx(t). Demodulator 560 demodulates signal SigRx(t) to produce a receive signal RX(t). Decoder 565 decodes signal RX(t) to recover received data Drx. As noted previously, the receive channel of radio 405 can be implemented using a simpler communication scheme, particularly if the receive-channel bandwidth is lower than that of the transmit channel. The receiver might be a simple, omni-directional radio-frequency (RF) link, for example.

[0025] Modem 500 additionally includes position-control circuitry 570 that controls the direction of antenna arrays 515 and 520 by application of position-control signals Xpos and Ypos to actuators 525. Position-control circuitry 570 derives control signals Xpos and Ypos from received data Drx in this embodiment.

[0026] Figure 6 is a state diagram 600 detailing the operation of position control circuitry 570 of Figure 7 in accordance with an embodiment that identifies alternative signal paths and automatically selects from among them to maintain signal integrity. The operation of state diagram 600 is illustrated in connection with system 400 of Figure 4. Position-control circuitry 132 of Figure 1 can operate in much the same way. The position control circuitry can be implemented using e.g. a dedicated state machine or an appropriately programmed microcontroller.

[0027] Beginning with state 605, radio 405 scans antenna arrays 515 and 520 over the available scan range while transmitting e.g. a training signal. Radio 410 responds to radio 405 with some indicia of receive quality to provide radio 405 with feedback relating direction to signal quality. Such feedback might be a measure of e.g. delay spread, signal strength, or mean amplitude variation. Should radio 405 exhaust the available scan range without receiving a response, state diagram 600 moves to state 610 and indicates a missing or failed link.

[0028] In the example of Figure 4, state 605 would identify the direct path for beam 430 as providing the strongest signal and alternative paths 450 and 455 as providing somewhat reduced but acceptable signal strengths. Position control circuitry 570 records the array coordinates (Xpos and Ypos) associated with the main and alternative paths and the process moves to state 615. Radio 405 is then ready to communicate with radio 410. In one embodiment, radio 405 sends high-definition video signals to radio 410.

[0029] Radio 410 sends radio 405 a return signal that may report on the quality (e.g., strength) of beam 430. The return signal can be continuous or periodic, and can be a dedicated alignment-control signal or can serve some alternative purpose. Further, as in the example of Figure 1, the return signal need not be demodulated or decoded to provide a measure of alignment. If in state 615 the return signal indicates a degradation in signal quality, the process moves to state 620 and radio 405 makes minor angular adjustments in an effort to improve the received signal quality. Radio 405 may additionally tune the alternative paths in state 615.

[0030] Returning to state 615, a total loss of signal (LOS) will cause the process to transition to state 625, in which case radio 405 will redirect the antenna array to select one or more alternative paths in an effort to reestablish communication. If the alternate paths fail, the process returns to state 605. If an alternative path reestablishes communication, then the process moves to step 620.

[0031] Figure 7 depicts a radio 700 in accordance with one embodiment that combines phase offsets with physical displacement for directional control of a receive antenna array 705 configured to receive a circularly polarized millimeter-wave radio signal. Radio 700 includes position control circuitry 710 and actuators 715 that control the physical displacement of antenna array 705 responsive to signals from a power detector 720. A quadrature demodulator 725 recovers in-phase and quadrature axis signals Ir(t) and Qr(t) from quadrature-basis received signal s(t) received by antenna array 705. Data-recovery circuit 730 recovers receive data Drx from signals Ir(t) and Qr(t), and may include a buffer to allow radio 700 time to switch between alternative signal paths in the event the received signal is lost or weakened. Quadrature demodulators are well understood by those of skill in the art so a detailed discussion is omitted for brevity.

[0032] Antenna array 705 includes N antennas 705[0:N-1], each of which is coupled to node s(t) via a respective phase shifter 750. The number N might be e.g. from four to twenty, and the antennas may be arranged in various configurations. The remaining elements of each antenna 705[N-1:0] are discussed above in connection with Figure 2. Phase control circuitry 755 is coupled to a control input of each phase shifter 750 via a respective control line PhC[N-1:0]. Radio 700 can thus adjust the effective receive direction of antenna array 705 by phase adjusting the signal contributions from each antenna 705[N-1:0]. The use of phase control circuitry in connection with antenna arrays is well understood. Briefly, the relative phases of the respective signals feeding an array of antennas are varied to reinforce (suppress) the effective radiation pattern in a desired (undesired) direction. The resulting radiation pattern can thus be shaped, or the receive sensitivity can be directionally selective. In this embodiment the provision for mechanical actuation increases the effective range of angles while reducing or eliminating the drive and control circuitry used for phase control.

[0033] The antenna array of Figure 7 receives circularly polarized waves, and a similar transmit antenna array may be used to transmit circularly polarized waves. In antenna theory, the term “polarization” refers to the orientation of an electric field of a wave with respect to the direction of wave propagation. For radio antennas, polarization is the sum of the E-plane orientations over time projected onto an imaginary planes along the direction of wave propagation. In the special case of circular polarization, an antenna or array of antennas continuously varies the electric field of a radio wave through all possible directions of its orientation with regard to the wave’s propagation. Circular polarization may be preferred in applications such as those detailed above in connection with Figure 4 because the resulting air interface is relatively insensitive to the orientation of communicating antennas along an axis normal to the beam; however, other embodiments can use different transmission schemes.

[0034] In the foregoing description and in the accompanying drawings, specific terminology and drawing symbols are set forth to provide a thorough understanding of the present invention. In some instances, the terminology and symbols may imply specific details that are not required to practice the invention. For example, the interconnection between circuit elements or circuit blocks may be shown or described as multi-conductor or single conductor signal lines. Each of the multi-conductor signal lines may alternatively be single-conductor signal lines, and each of the single-conductor signal lines may alternatively be multi-conductor signal lines. Signals and signaling paths and antennae shown or described as being single-ended may also be differential, and vice-versa.

[0035] While the present invention has been described in connection with specific embodiments, variations of these embodiments will be obvious to those of ordinary skill in the art. For example:

- Antenna arrays of the type discussed above can employ various modulation schemes that vary phase, amplitude, or frequency to convey information.
- Directional antennas and antenna arrays can use antennas and antenna elements of various shapes, such as patch or loop antenna elements.
- Directional beams can be conveyed using static or rotating polarization, and rotating polarization can be circular or elliptical. Still other beam shapes can be used.
- Various radio conversion types, such as zero-intermediate-frequency or heterodyne conversion types, can be used.
- Transmitted data can be expressed using digital or analog signals.

Moreover, some components are shown directly connected to one another while others are shown connected via intermediate components. In each instance the method of interconnection, or "coupling," establishes some desired electrical communication between two or more circuit nodes, or terminals. Such coupling may often be accomplished using a number of circuit configurations, as will be understood by those of skill in the art. Therefore, the spirit and scope of the appended claims should not be limited to the foregoing description.

Only those claims specifically reciting “means for” or “step for” should be construed in the manner required under the sixth paragraph of 35 U.S.C. §112.

CLAIMS

What is claimed is:

1. A radio comprising:

   a. a signal node to communicate a signal having a carrier frequency within a range of forty gigahertz to one hundred twenty gigahertz;

   b. an antenna array having a plurality of antennas, each antenna coupled to the signal node;

   c. a substrate supporting the antenna array; and

   d. an actuator connected to the substrate and the antenna array, the actuator including an elastomeric material disposed between conductive layers, wherein the actuator deforms in response to a control voltage applied between the conductive layers

2. The radio of claim 1, further comprising a modulator coupled to the signal node to modulate the signal, wherein the antenna array broadcasts a millimeter-wave electro-magnetic signal responsive to the first-mentioned signal.

3. The radio of claim 1, further comprising, for each antenna, a phase-shifter coupled between the signal node and the antenna.

4. The radio of claim 1, further comprising a demodulator coupled to the signal node to demodulate the signal, wherein the antennas are sized to produce the first-mentioned signal responsive to a millimeter-wave electromagnetic beam.

5. The radio of claim 1, further comprising position-control circuitry coupled to the actuator, the position-control circuitry to develop the control voltage.

6. The radio of claim 5, further comprising a signal-quality monitor coupled between the signal node and the position-control circuitry, the signal-quality monitor to issue measures of signal quality.

7. The radio of claim 5, wherein the array is disposed at an angle with respect to the substrate, wherein the actuator varies the angle responsive to the control voltage, and wherein the position-control circuitry derives the control voltage from the measures of signal quality.

8. The radio of claim 5, wherein the antenna array derives the measures of signal quality from an electromagnetic beam, and wherein the position-control circuitry issues the control voltage to track the beam.

9. The radio of claim 5, wherein the position-control circuitry includes a state machine, and wherein the state machine records main and auxiliary array coordinates.

10. The radio of claim 5, wherein the position-control circuitry switches the antenna array from the main array coordinates to the auxiliary array coordinates responsive to a loss of the signal.

11. The radio of claim 1, wherein each of the antennas includes polarized antenna elements.

12. The radio of claim 1, wherein each antenna comprises a dipole.

13. The radio of claim 12, wherein each antenna comprises perpendicular dipoles.

14. The radio of claim 1, wherein the carrier frequency is from forty gigahertz to ninety gigahertz.

15. A method comprising:

- communicating a millimeter electro-magnetic beam between first and second antennas, wherein at least one of the first and second antennas is a directional antenna array;
- stimulating an electroactive polymer attached to the antenna array to actuate the antenna array over a scan range; and
- measuring a quality of the beam at one of the first and second antennas over the scan range.

16. The method of claim 15, wherein the quality of the beam includes a measure of receive power.

17. The method of claim 15, further comprising storing a plurality of antenna positions over the scan range for which the quality of the beam exceeds a threshold quality.

18. The method of claim 17, further comprising sensing a loss of the beam at a first of the antenna positions and, responsive to the sensing, redirecting the antenna array to a second of the antenna positions.

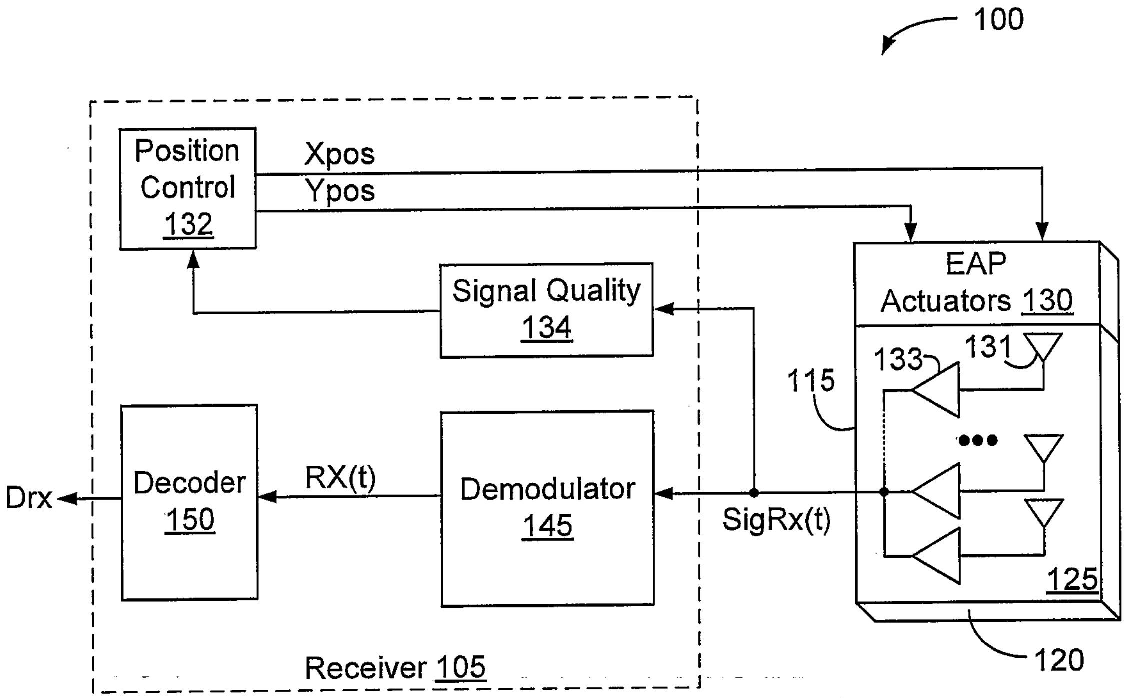
19. The method of claim 18, wherein the redirecting comprises stimulating the electroactive polymer.

20. A radio comprising:

a. a signal node to communicate a signal having a carrier frequency within a range of forty gigahertz to one hundred twenty gigahertz;

b. directional antenna means coupled to the signal node; and

c. an actuator connected to the antenna means, the actuator including an elastomeric material disposed between conductive layers, wherein the actuator deforms in response to a control voltage applied between the conductive layers.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Drx
SigRx(t)
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120
Receiver 105

Fig. 1

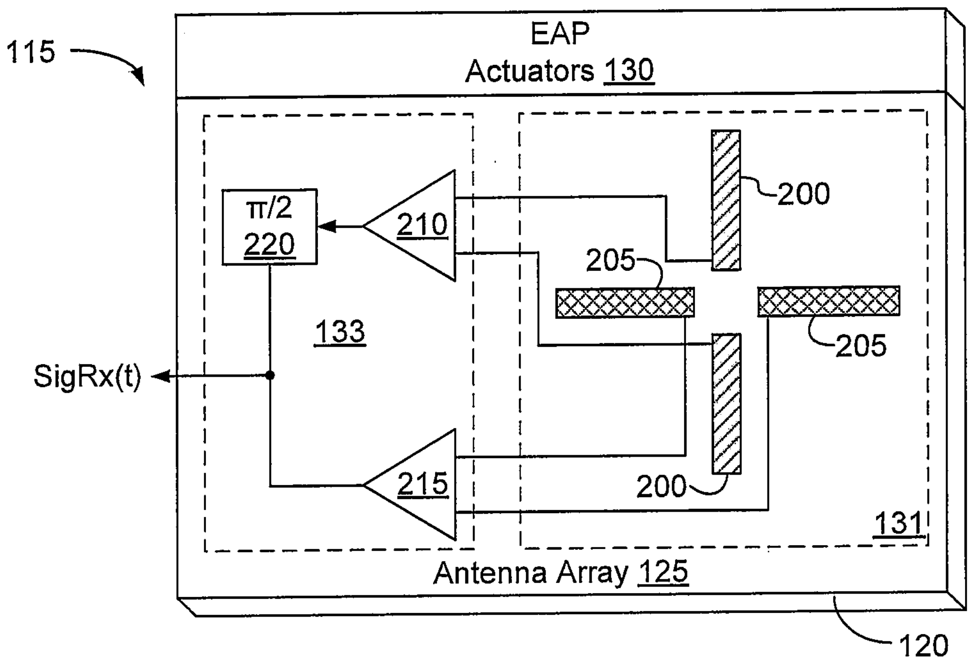
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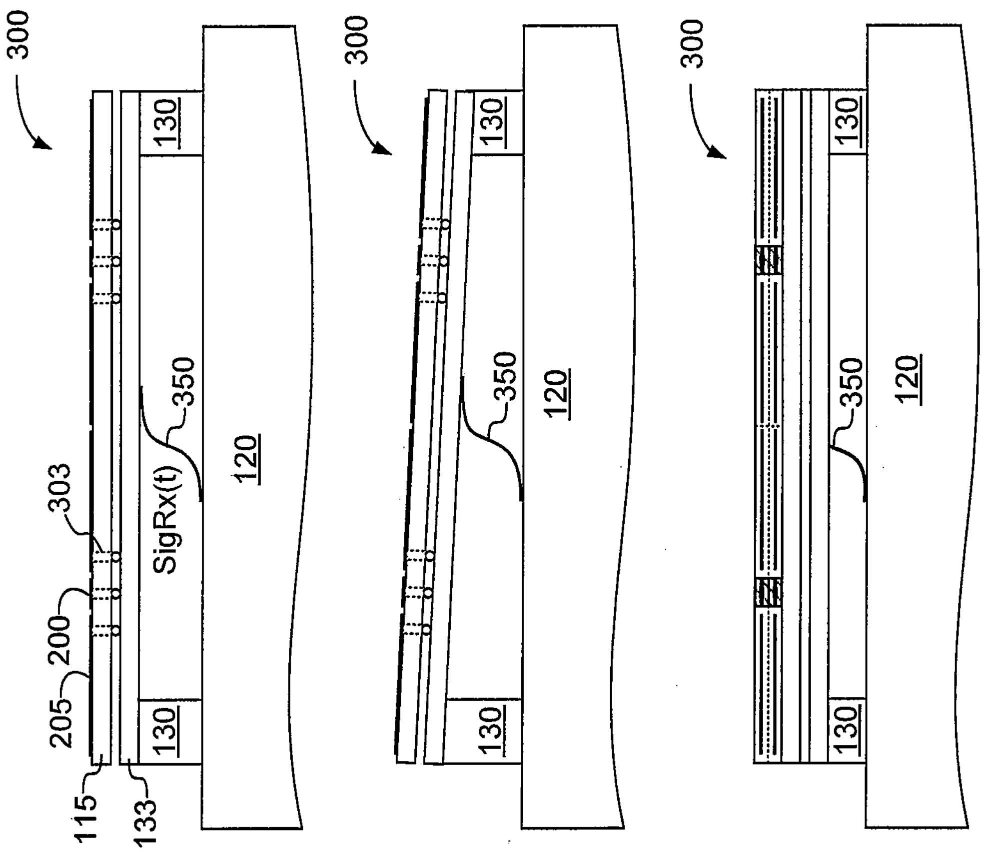
Fig. 2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120
130

Fig. 3B

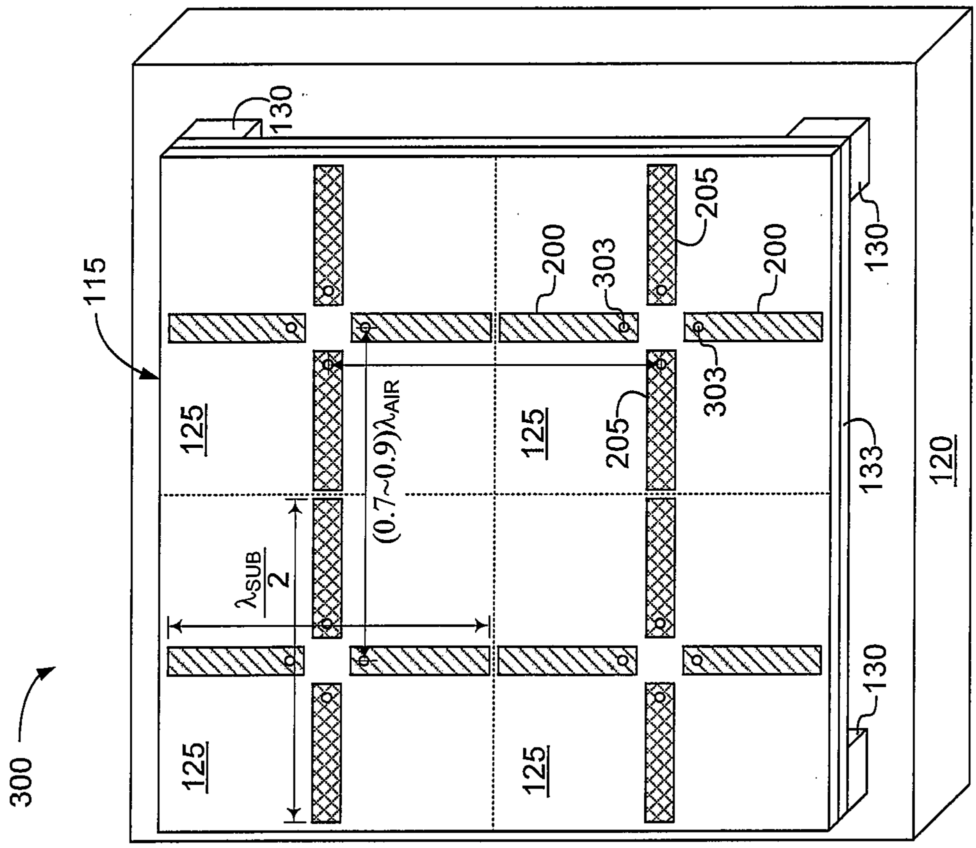
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Fig. 3A

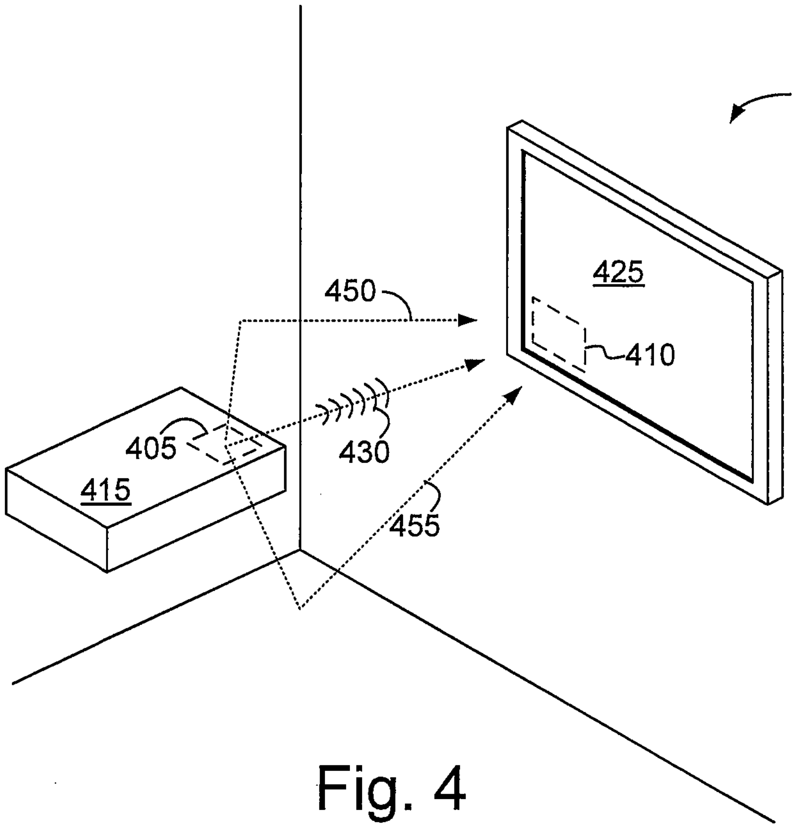
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Fig. 4

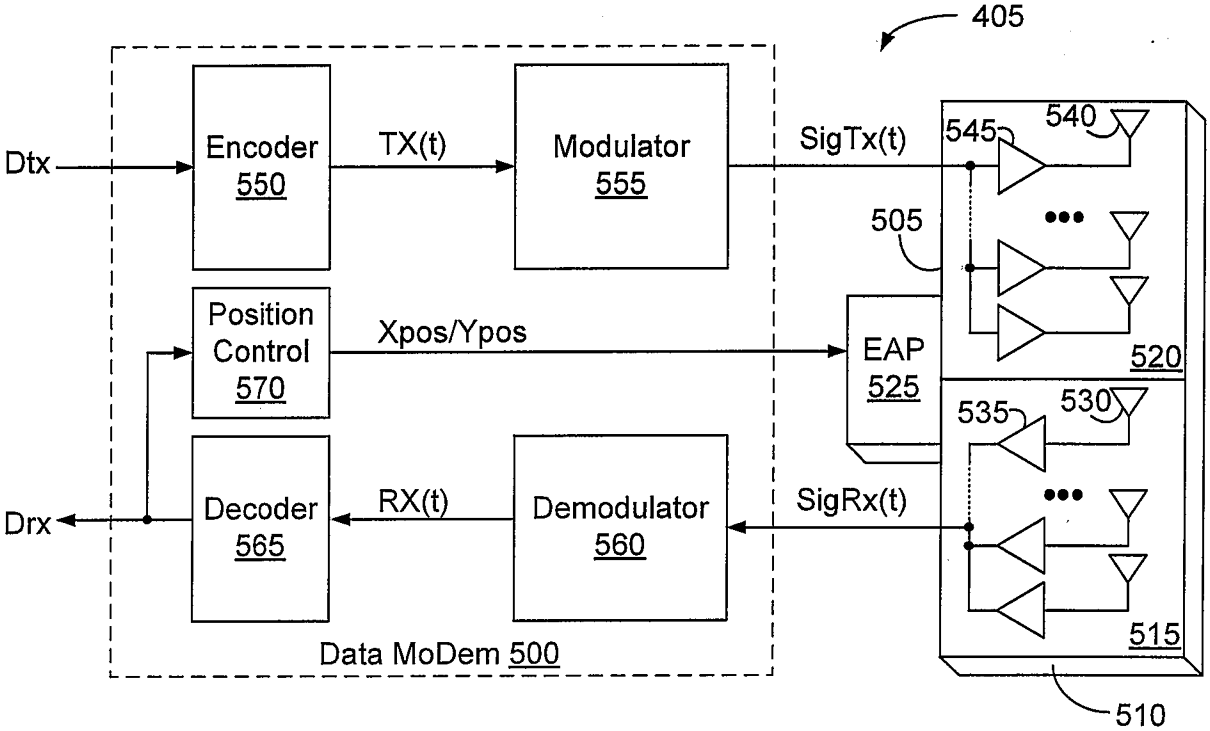
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Fig. 5

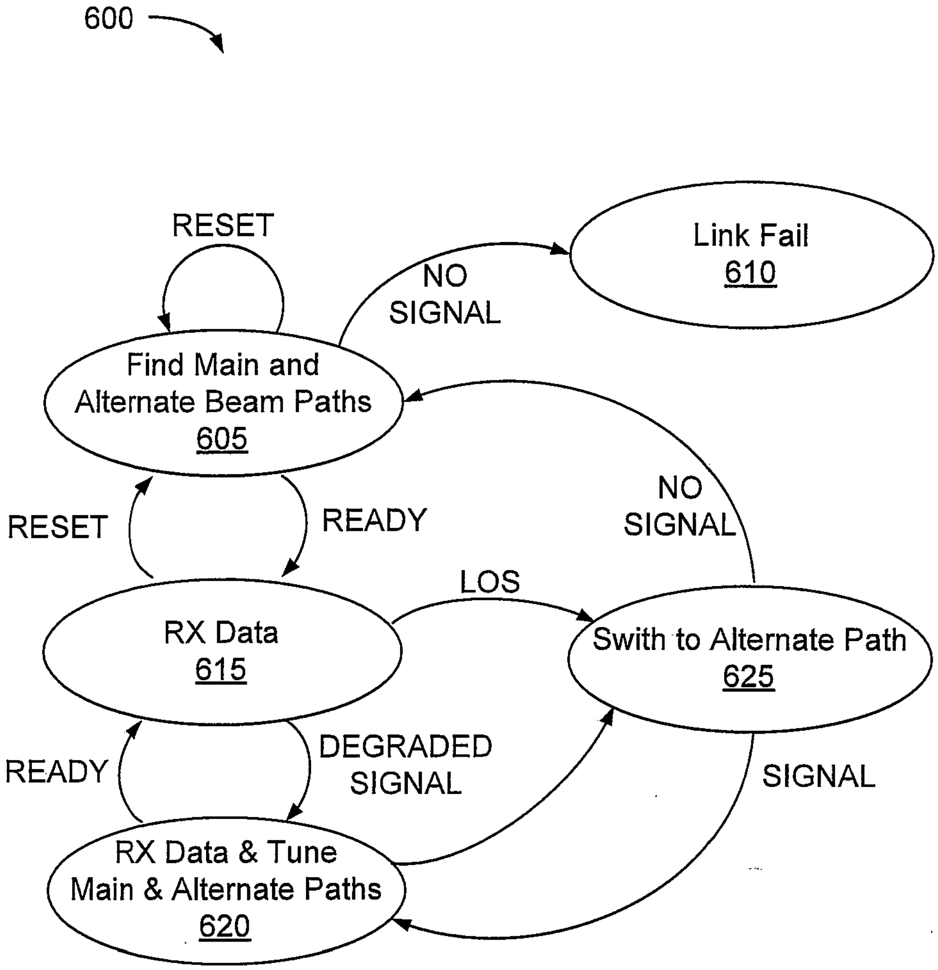
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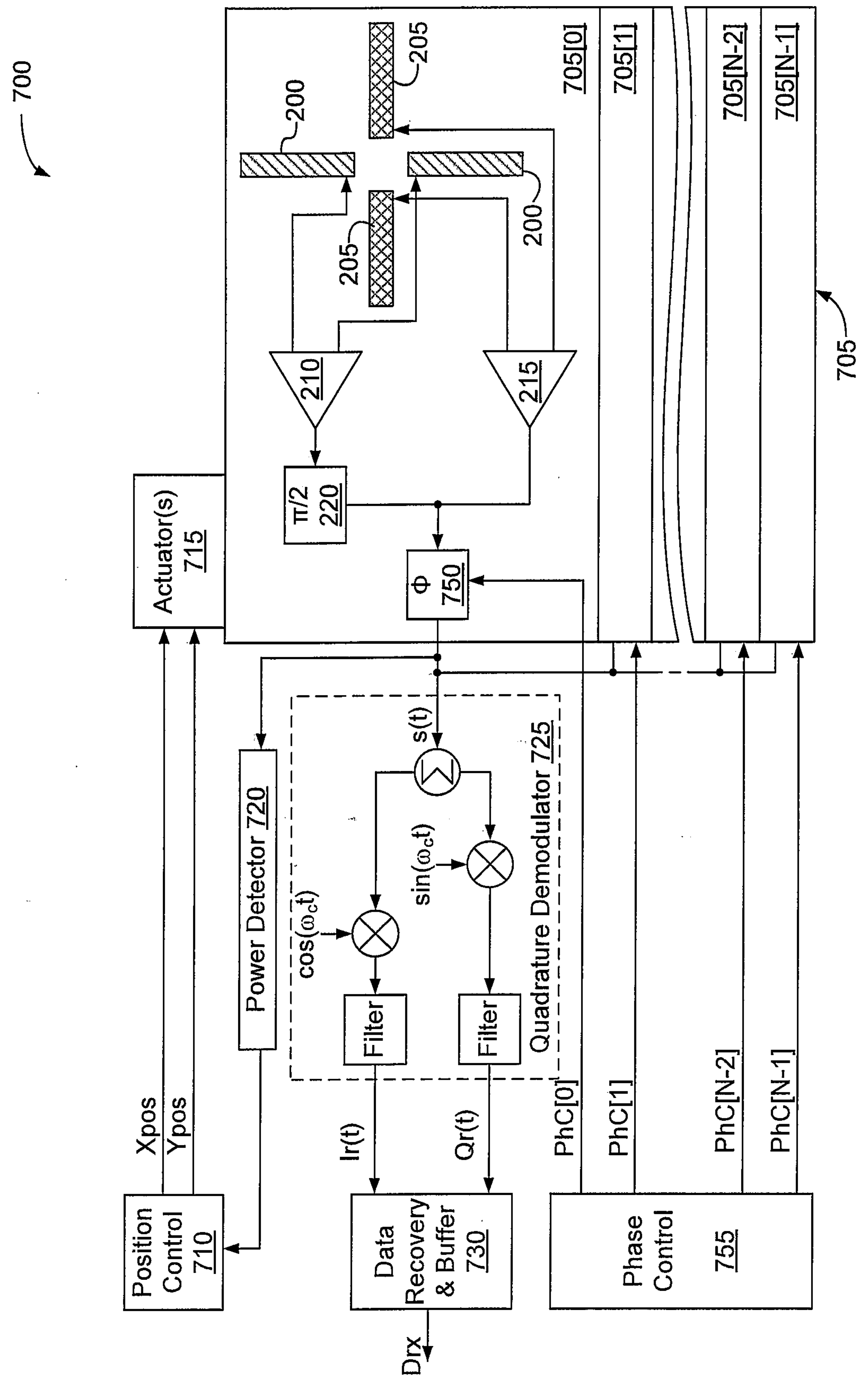
Fig. 6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715
Power Detector 720
s(t)
cos(ωct)
sin(ωct)
Filter
Filter
Quadrature Demodulator 725
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Ypos
Ir(t)
Qr(t)
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PhC[N-2]
PhC[N-1]
Position Control 710
Data Recovery & Buffer 730
Drx
Phase Control 755

Fig. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/070286

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01Q1/12 H01Q3/02 H01Q21/06

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)
H01Q

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

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

EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CHANG-WOOK BAEK ET AL: "A V-BAND MICROMACHINED 2-D BEAM-STEERING ANTENNA DRIVEN BY MAGNETIC FORCE WITH POLYMER-BASED HINGES" IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 1, no. 51, 1 January 2003 (2003-01-01), pages 325-331, XP001141826 ISSN: 0018-9480	1-14,20
Y	the whole document	15-19

Y	US 2002/090941 A1 (ZHANG FRANKLIN ZHIGANG [US]) 11 July 2002 (2002-07-11) paragraphs [0043] - [0057]	15-19

	-/--	

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

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
28 October 2008	05/11/2008

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

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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Information on patent family members

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