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(54) Title: MULTI-ELEMENT COUPLER FOR GENERATION OF ELECTROMAGNETIC ENERGY

(57) Abstract: Implantable devices and/or sensors can be wirelessly powered by controlling and propagating electromagnetic waves in a patient's tissue. Such implantable devices/sensors can be implanted at target locations in a patient, to stimulate areas such as the heart, brain, spinal cord, or muscle tissue, and/or to sense biological, physiological, chemical attributes of the blood, tissue, and other patient parameters. The propagating electromagnetic waves can be generated with sub-wavelength structures configured to manipulate evanescent fields outside of tissue to generate the propagating waves inside the tissue. Methods of use are also described.

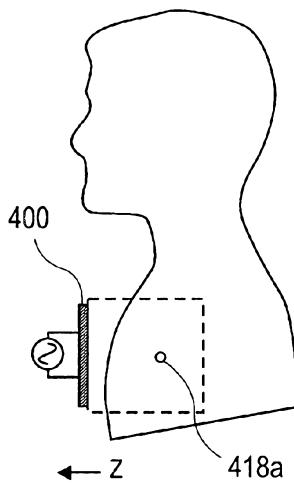


FIG. 4A



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**MULTI-ELEMENT COUPLER FOR
GENERATION OF ELECTROMAGNETIC ENERGY**

CROSS REFERENCE TO RELATED APPLICATIONS

5 [0001] This application claims the benefit of U.S. Provisional Appln. No. 61/878,436, filed September 16, 2013, titled “Multi-Element Coupler”, and U.S. Provisional Appln. No. 61/913,164, filed December 6, 2013, titled “Power Management and Conversion for Medical Implants”, both of which are incorporated herein by reference.

10 **INCORPORATION BY REFERENCE**

[0002] All publications and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication or patent application was specifically and individually indicated to be incorporated by reference.

15 **FIELD**

[0003] This disclosure is related generally to wireless power transfer. More specifically, this disclosure relates to delivering wireless power through tissue into a device implanted in a human or animal.

20 **BACKGROUND**

[0004] Systems and methods that supply power without electrical wiring are sometimes referred to as wireless energy transmission (WET). Wireless energy transmission greatly expands the types of applications for electrically powered devices. Implantable medical devices typically require an internal power source able to supply adequate power for the reasonable lifetime of the device or an electrical cable that traverses the skin.

[0005] More recently there has been an emphasis on systems that supply power to an implanted device without using transcutaneous wiring, sometimes referred to as a Transcutaneous Energy Transfer System (TETS). Frequently energy transfer is accomplished using two magnetically coupled coils set up like a transformer so power is transferred magnetically across the skin. Conventional systems are relatively sensitive to variations in position and alignment of the coils, typically requiring the coils to be physically close together and well aligned.

[0006] Existing systems that transmit power wirelessly based on magnetic fields typically operate in the near-field only, where the separation of the transmitter and receiver coils is less than or equal to the dimension of the coils.

[0007] Wireless powering has long been of interest for enhancing the function of implantable electronics, beginning in the early 1960's with experiments in transporting electromagnetic energy across the chest wall. Drawing conceptually on schemes for transferring power over air through objects coupled in the near-field, early manifestations involved bulky coils tether to 5 vacuum tube power supplies or battery cells that posed severe challenges for long-term operation in the body. Advances in semiconductor technology have since enabled sophisticated devices that incorporate sensing and stimulation capabilities within cellular-scale dimensions. Nearly all existing systems, however, continue to require large structures for energy storage or harvesting, often several centimeters in the largest dimension with overall size, weight, and efficiency 10 characteristics that constrain opportunities for integration into the body.

[0008] Near-field approaches rely on strong coupling occurring between objects with matched electrical characteristics, such as resonances and impedances. These near-field approaches do not generalize easily to geometries with extreme size asymmetry, while far-field transfer is limited by absorption over surfaces of the body.

[0009] The present disclosure describes methods and apparatus for wireless power transfer 15 that overcome the limitations of previous wireless power transfer methods. The present disclosure provides a mid-field approach in which both evanescent and radiative components of a structure are coupled to modes in tissue that transport energy continuously away from the source. Interference resulting from phase differences between these components affords 20 additional opportunity for spatially focused and dynamically adjustable field patterns inside tissue. The level of performance obtainable from the approach described in this disclosure can exceed requirements for advanced monitoring and control capabilities for applications in medicine, neuroscience, or human-machine interfaces.

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SUMMARY

[0010] In one embodiment, a wireless power system is provided, comprising an external module having one or more sub-wavelength structures configured to transmit wireless power by manipulating evanescent fields outside of tissue to generate propagating fields inside the patient's tissue and thereby generate a spatially focused field in tissue, and an implantable 30 module configured to receive the wireless power from the external module, the implantable module including at least one sensor or stimulator configured to sense a parameter of the tissue or apply stimulation to the tissue.

[0011] In some embodiments, the at least one sensor is selected from the group consisting of 35 a thermal sensor, a chemical sensor, a pressure sensor, and oxygen sensor, a PH sensor, a flow sensor, an electrical sensor, a strain sensor, a magnetic sensor, and an imaging sensor.

[0012] In other embodiments, the at least one stimulator is selected from the group consisting of an electrical stimulator, an optical stimulator, a chemical stimulator, and a mechanical stimulator.

5 [0013] In one embodiment, the implantable device comprises a modular design that allows interchangeable sensors and/or stimulators.

[0014] In some embodiments, the one or more sub-wavelength structures are selected from the group consisting of a patch, a PIFA, a slot in a ground plane, a cross slot in a ground plane, an aperture coupled circular slot in a ground plane, and a half slot in a ground plane.

10 [0015] In another embodiment, the external module further comprises one or more excitation ports coupled to the one or more sub-wavelength structures, at least one voltage source coupled to the one or more excitation ports, and a controller configured to adjust a phase and/or an amplitude delivered to the one or more sub-wavelength structures to adjust a position of a focal point of the spatially focused field in the tissue.

15 [0016] In one embodiment, the controller is configured to detect a power level of received wireless energy from the implanted module, and is configured to provide feedback to automatically adjust the position of the focal point to optimize wireless power transmission.

[0017] In another embodiment, the implantable module is configured to be implanted on, in, or near a heart to apply leadless pacing to the heart.

20 [0018] In some embodiments, the implantable module is configured to be implanted on, in, or near a brain to apply deep brain stimulation to the brain. In another embodiment, the implantable module is configured to be implanted on, in, or near a spinal cord to apply stimulation to the spinal cord. In yet another embodiment, the implantable module is configured to be implanted on, in, or near a muscular tissue of the tongue to apply stimulation to the tongue to treat obstructive sleep apnea.

25 [0019] A method of providing therapy to a patient is provided, comprising implanting a wireless power receiving in the patient, transmitting a mid-field propagating wave to the wireless power receiving module to power the module, sensing a parameter of the patient with the wireless power receiving module, and providing a therapy to the patient with the wireless power receiving module based on the sensed parameter.

30 [0020] In some embodiments, the transmitting step further comprises manipulating evanescent fields outside of the patient's tissue to generate propagating fields inside the patient's tissue and thereby generate a spatially focused field in the tissue.

[0021] A method of cardiac pacing in a patient is also provided, comprising implanting a wireless power receiving module in, on, or near a heart, transmitting a mid-field propagating wave to the wireless power receiving module to power the module, sensing a parameter of the

heart with the wireless power receiving module, and providing electrical pacing to the heart with the wireless power receiving module based on the sensed parameter.

[0022] In some embodiments, the transmitting step further comprises manipulating evanescent fields outside of the patient's tissue to generate propagating fields inside the patient's tissue and thereby generate a spatially focused field in the tissue.

[0023] A method of deep brain stimulation is also provided, comprising implanting a wireless power receiving module in, on, or near a brain, transmitting a mid-field propagating wave to the wireless power receiving module to power the module, sensing a parameter of the brain with the wireless power receiving module, and providing stimulation to the brain with the wireless power receiving module based on the sensed parameter.

[0024] In some embodiments, the transmitting step further comprises manipulating evanescent fields outside of the patient's tissue to generate propagating fields inside the patient's tissue and thereby generate a spatially focused field in the tissue.

[0025] A method of stimulating tissue is provided, comprising implanting a wireless power receiving module into tissue, transmitting a mid-field propagating wave to the wireless power receiving module to power the module, sensing a parameter of the tissue with the wireless power receiving module, and providing stimulation to the tissue with the wireless power receiving module based on the sensed parameter.

[0026] In some embodiments, the transmitting step further comprises manipulating evanescent fields outside of the patient's tissue to generate propagating fields inside the patient's tissue and thereby generate a spatially focused field in the tissue.

[0027] In another embodiment, the method further comprises adjusting a focal point of the propagating wave to optimize wireless power transmission to the module.

[0028] In another embodiment, the transmitting step comprises transmitting the wave with a sub-wavelength structure that produces a magnetic field perpendicular to the wave and parallel to a tissue interface.

[0029] An apparatus configured to transfer wireless power through tissue is provided, comprising a substrate, at least one sub-wavelength structure disposed on the substrate, at least one radio-frequency port coupled to the at least one sub-wavelength structure, a voltage or current source coupled to the at least one radio-frequency port, and a controller configured to manage excitation of the at least one radio-frequency port and sub-wavelength structure with the voltage or current source to manipulate evanescent fields outside of tissue to generate propagating fields inside the tissue and thereby generate a spatially focused field in the tissue.

[0030] In some embodiments, each of the at least one sub-wavelength structure is coupled to a respective independent radio-frequency port.

[0031] An apparatus configured to transfer wireless power through tissue is also provided, comprising a plurality of sub-wavelength structures configured and arranged to generate propagating fields inside tissue and thereby generate a spatially adaptable electromagnetic field in the tissue, a plurality of independent feed ports configured and arranged to individually excite 5 a respective one of the plurality of sub-wavelength structures thereby generating the spatially adaptable electromagnetic field, and a controller configured to redistribute a peak surface electromagnetic field to increase an allowable radio frequency output power.

[0032] In some embodiments, the plurality of sub-wavelength structures are further configured and arranged to generate an adaptive steering field in tissue.

10 [0033] In other embodiments, the spatially focusing and adaptive steering field/signal has a frequency between 300 MHz and 3000 MHz.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] The novel features of the invention are set forth with particularity in the claims that 15 follow. A better understanding of the features and advantages of the present invention will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which the principles of the invention are utilized, and the accompanying drawings of which:

[0035] FIGS. 1A-1N show various embodiments of an external wireless power transmitting 20 module.

[0036] FIG. 2 shows the magnetic field that results from a conventional inductively coupled loop source.

[0037] FIG. 3A shows the magnetic field that results from a patch sub-wavelength structure.

[0038] FIG. 3B shows the magnetic field that results from a PIFA sub-wavelength structure.

25 [0039] FIG. 3C shows the magnetic field that results from an aperture coupled circular slot sub-wavelength structure.

[0040] FIG. 3D shows the magnetic field that results from a cross slot sub-wavelength structure.

[0041] FIG. 3E shows the magnetic field that results from a half slot sub-wavelength 30 structure.

[0042] FIG. 4A shows an implanted device in a human patient being wirelessly powered by a mid-field propagating wave technique.

[0043] FIGS. 4B-4C show wireless power transmission with an inductively coupled approach (FIG. 4B) and a mid-field propagating wave approach (FIG. 4C).

[0044] FIGS. 5A-5B are schematic diagrams of architectures for a controller of the external module of FIGS. 1A-1N.

[0045] FIG. 6 shows one embodiment of an implanted device configured to receive wireless power from the external module of FIGS. 1A-1N.

5 [0046] FIGS. 7A-7C show embodiments of architectures for a controller of the implanted device of FIG. 6.

DETAILED DESCRIPTION

[0047] Implantable devices and/or sensors can be wirelessly powered by controlling and propagating electromagnetic waves in a patient's tissue. Such implantable devices/sensors can be implanted at target locations in a patient, as non-limiting examples, to stimulate areas such as the heart, and/or to sense biological, physiological, chemical attributes of the blood, tissue, and other patient aspects. Difficulties in achieving wireless power transfer can occur in the mismatch between the size of the implantable devices/sensors and the power transfer source, the depth of the devices/sensors in a patient, and additionally the spatial arrangement of the devices/sensors relative to the power transfer source.

[0048] Various aspects of the present disclosure are directed toward apparatuses or methods as exemplified or supported by aspects of the above noted description/embodiments, as well as the description/embodiments of the attached appendices. For instance, certain embodiments of the present disclosure are directed to manipulation of evanescent fields outside a patient's tissue to excite/control propagating fields inside the patient's tissue and thereby generate a spatially focusing and adaptive steering field/signal in the tissue.

[0049] Each of the sub-wavelength structures described above can be connected to a respective port in order to manipulate evanescent fields to excite/control propagating fields inside a patient's tissue. These propagating fields can be further manipulated to generate a spatially focusing and adaptive steering field/signal in the tissue. Any sub-wavelength structure that yields transverse magnetic fields dominating near the source, will minimize the tissue heating effect. These sub-wavelength structures can be configured to generate a magnetic near field that is in parallel with the tissue interface, and that is perpendicular with the propagating wave that transmits wireless energy. In certain embodiments, as shown above, an arrangement can include one, two, three, or four or more sub-wavelength structures are used to manipulate the evanescent fields. In other embodiments, two or more of the arrangements shown above can be combined such that even more sub-wavelength structures (e.g., six, eight, twelve) are used to manipulate the evanescent fields.

[0050] In certain embodiments, an arrangement can include two, three, four, or more sub-wavelength structures that can be configured to manipulate the evanescent fields. In other embodiments, two or more of the arrangements shown above can be combined such that even more sub-wavelength structures (e.g., six, eight, twelve, or more) are used to manipulate the 5 evanescent fields.

[0051] Various aspects of the present disclosure include apparatus and methods directed to 10 multiple sub-wavelength structures configured to generate a spatially adaptable electromagnetic field/signal (e.g., a midfield electromagnetic field) in a patient's tissue. The sub-wavelength structures can each be connected to an independent feed port that individually excites a respective one of the sub-wavelength structures, thereby generating the spatially adaptable 15 electromagnetic field/signal. The independent feed ports and the sub-wavelength structures are adapted to redistribute the peak surface electromagnetic fields in order to increase the allowable radio frequency output power in accordance with regulations from the apparatus.

[0052] In certain embodiments, the sub-wavelength structures manipulate evanescent fields 15 to excite/control propagating fields and thereby generate a spatially focusing and adaptive steering field/signal in tissue.

[0053] Various aspects of the present disclosure include apparatus and methods directed to 20 multiple sub-wavelength structures that generate and receive a spatially adaptable electromagnetic field/signal, which may include a power signal and a communication data signal. Additionally, aspects of the present disclosure may also include multiple sub-wavelength structures that generate a spatially adaptable electromagnetic field/signal and to provide and receive a spatially adaptable electromagnetic signal in multiple frequency bands.

[0054] Certain aspects of the present disclosure are also directed toward implantable devices 25 that receive power transmitted via the sub-wavelength structures that transmit a spatially adaptable electromagnetic field. The implantable device, consistent with various aspects of the present disclosure, can be a size such that the device is deliverable via a catheter, cannula, or a needle. Additionally, the implantable device(s) can include a coil that receives the energy from the spatially adaptable electromagnetic field. In such an embodiment, the spatially adaptable electromagnetic field/signal is received as magnetization due to current in the coil. Further, the 30 implantable devices can also include, in certain instances, a multi-turn coil that receives the spatially adaptable electromagnetic signal, rectifying circuitry that converts the spatially adaptable electromagnetic signal using AC-DC power conversion, and control circuitry to regulate pulse amplitudes, duration, and frequency.

[0055] Additionally, in certain embodiments, the sub-wavelength structures, consistent with 35 various aspects of the present disclosure, adjust an operating frequency of the spatially adaptable

electromagnetic signal to adjust the power of the implantable device or sensor. In some embodiments, the spatially adaptable electromagnetic signal can have frequency between 300 MHz and 3000 MHz.

[0056] Various aspects of the present disclosure are directed toward powering of one or more active implantable sensors or devices using a single power source. The types of implantable devices/sensors that can be powered using the single power source, consistent with various aspects of the present disclosure, are numerous. For instance, the implantable devices can be used for muscular stimulation, stimulation/sensing to regulate a patient's heart beat, multisite deep brain stimulation, drug delivery, and/or biological, physiological, and chemical sensing.

[0057] The devices disclosed herein can be individually addressable and independently controlled. Thus, the devices, for example as those used for muscular stimulation, can be placed at different locations corresponding to different muscle groups, and perform stimulation in a synchronized manner. Similarly, brain stimulation devices can be placed at different locations in the brain, and stimulation can be performed in a synchronized manner. The same can be said with drug delivery devices. Moreover, because the devices can be individually addressable and independently controlled, the devices can be activated and/or powered asynchronously as well as synchronously. These devices, in certain instances, can have characteristics dimensions in that the devices are much smaller (e.g., one, two, or three orders of magnitude) than their depth in tissue. Similarly, the devices, in certain instances, can have characteristics dimensions in that the devices are much smaller (e.g., one, two, or three orders of magnitude) than the source that provides the power to the devices.

[0058] The aspects of the present disclosure, as directed toward apparatuses, devices, and methods, can be utilized alone or in combination with various other aspects.

[0059] The structures described herein can be used with sensors/devices that include feedback to the sub-wavelength structures. These types of sensors can include, for example, implantable temperature sensors or imaging devices. In this manner, the devices are responsive to the structures illustrated above that generate a spatially adaptable electromagnetic field/signal. The feedback-type devices respond to the power and/or data portions of the signal provided by the spatially adaptable electromagnetic field/signal, and are prompted to respond. For instance, temperature sensors located in a patient will broadcast/report the temperature of the tissue in response to the power and/or data portions of the signal provided by the spatially adaptable electromagnetic field/signal. Additionally, imaging devices implanted in a tissue can broadcast/report the captured images in response to the power and/or data portions of the signal provided by the spatially adaptable electromagnetic field/signal. Moreover, the penetration depth of the spatially adaptable electromagnetic field/signal can be modeled and controlled.

Thus, in certain embodiments, the feedback devices can indicate and label data, in response to the spatially adaptable electromagnetic field/signal, to record the depth at which the device is operating. By storing this data on a patient-by-patient basis in a storage device, a computer can access and analyze this data for statistical purposes.

5 [0060] By storing the position or label of the feedback-type device in a memory circuit via a programmable computer, various patient feedback tracking methods can also be realized. For instance, the depth of an implantable imaging device can be optimized by analyzing the surrounding tissue. In this manner, the depth of the implantable imaging device can be adjusted if it is determined that a more optimal position is possible. Similarly, the depth of an implantable
10 stimulation device can be used to determine the health of the tissue area surrounding the stimulation device, and determine an optimal positioning of the device in response to the spatially adaptable electromagnetic field/signal. Additionally, the feedback-type devices can respond to the spatially adaptable electromagnetic field/signal and broadcast data stored in a memory circuit. Thus, the feedback-type devices can continuously update a physician of the data
15 that is being tracked by the device. This allows for real-time monitoring, diagnosing, and/or treating a patient wirelessly.

[0061] Implantable devices/sensors can be wirelessly powered by controlling and propagating electromagnetic waves in tissue. The implantable devices can be implanted in humans or in other animals such as pets, livestock, or laboratory animals such as mice, rats, and
20 other rodents. Such implantable devices/sensors can be implanted at target locations in a patient, as non-limiting examples, to stimulate areas such as the heart, and/or to sense biological, physiological, chemical attributes of the blood, tissue, and other patient aspects. Difficulties in achieving wireless power transfer can occur in the mismatch between the size of the implantable devices/sensors and the power transfer source, the depth of the devices/sensors in a patient, and
25 additionally the spatial arrangement of the devices/sensors relative to the power transfer source.

[0062] Various aspects of the present disclosure are directed toward apparatuses or methods as exemplified or supported by aspects of the above noted description/embodiments, as well as the description/embodiments of the attached appendices. For instance, certain embodiments of the present disclosure are directed to manipulation of evanescent fields outside a patient's tissue
30 with sub-wavelength structures to excite/control propagating fields inside the patient's tissue and thereby generate a spatially focusing and adaptive steering field/signal in the tissue. A sub-wavelength structure generates fields that are evanescent in nature near the source. In contrast, in conventional wireless approaches using inductive coupling, the evanescent components outside tissue (near the source) remain evanescent inside tissue which does not allow for
35 effective depth penetration.

[0063] This disclosure provides embodiments of sub-wavelength structures and methods for controlling the excitation of those structures to excite the propagating modes inside tissue from the evanescent modes outside tissue. As a result, this approach is very effective in transporting energy to absorption-limited depth inside tissue. The designs disclosed herein include structures that use tissue as a dielectric waveguide to tunnel energy into the body. The energy can be received by an implanted module which will be discussed below, to allow for wireless power transfer to implanted devices at depths unattainable with conventional inductive coupling technology.

[0064] This disclosure provides a midfield wireless powering approach that integrates an external module configured to transmit wireless power, and one or more implanted modules configured to receive wireless power that combines an impulse generator and at least one stimulation electrode together into a small, leadless, implantable device. In some embodiments, the implanted module can be small enough to be delivered via a catheter or a hypodermic needle. For example, the implanted module can be as small as a few millimeters in diameter (2-3mm) down to having diameters on the order of 100's of microns or less. This implanted module allows for the transfer of wireless power to nearly any location in the body at performance levels far exceeding requirements for both complex electronics and physiological stimulation. Because the implanted modules are small, they can be injected into the targeted nerve or muscle region directly without the need for leads and extensions, to provide sensing and stimulation to the targeted nerve, muscle, or tissue region.

[0065] For illustrative purposes, FIGS. 1A-1N show various embodiments and views of wireless power transmitting modules 100, including one or more sub-wavelength structures 102, consistent with various aspects of the present disclosure. A sub-wavelength is defined with respect to the wavelength of the field outside a patient's tissue or in the air. A sub-wavelength structure can be of a dimension less than the wavelength in air but might be comparable to the wavelength in tissue. For example, at 1.6 GHz, the wavelength in muscle is about 7.3 times smaller than the wavelength in air. Any source structure that is of dimension on the order of the wavelength in muscle or tissue may be a sub-wavelength structure. FIGS. 1C-1E show perspective views of three specific embodiments of wireless power transmitting modules, and FIGS. 1F-1H show side views of those modules, respectively. Similarly, FIGS. 1I-1K show perspective views of some wireless power transmitting modules, and FIGS. 1L-1N show side views of those modules, respectively.

[0066] The sub-wavelength structures of FIGS. 1A-1N can be configured to manipulate evanescent fields outside a patient's tissue to excite/control propagating fields inside the patient's tissue to generate a spatially focusing and adaptive steering field/signal in the tissue. The

wireless power transmitting modules 100 shown in FIGS. 1A-1N can include the sub-wavelength structure(s) 102 disposed over a substrate 104 and one or more ground plane(s) 106 (shown in the side views of FIGS. 1F-1H and 1L-1N. In some embodiments, the sub-wavelength structures 102 can comprise a conductive material, such as a copper. The substrate can comprise an insulating material, such as an epoxy, or a ceramic. The substrate can be a solid, rigid, substrate, or alternatively can be a flexible substrate configured to conform to the skin surface of patients. In some embodiments, the sub-wavelength structures 100 can further comprise a ground plane bonded to or disposed on the substrate. The ground plane can be disposed on a top surface (FIGS. 1H, 1L, 1N), a bottom surface (FIGS. 1F, 1G), or both top and bottom surfaces (FIG. 1M) of the substrate.

[0067] The design of each sub-wavelength structure can be varied depending on the design requirements of the specific application. FIGS. 1A-1B both show a wireless power transmitting module having a plurality of sub-wavelength structures 102, wherein the sub-wavelength structures resemble X' with curved or protruding strips or features. In both these embodiments, each of the sub-wavelength structures 102 can be excited by one or more independent radio-frequency ports 103 connected to a voltage and/or current source. In some embodiments, the sub-wavelength structures can be excited with a voltage ranging from 0.1 V to 10's V, or can be excited with a current ranging from 0.1 A to 10's A. The frequency range of the source can range from 300 MHz to 3 GHz. For appropriate phases between the port signals, the sub-wavelength structures can generate circular current paths that mimic the optimal current density. When positioned above tissue, the structures couple power from the external circuitry into the tissue volume with high efficiency (>90%), as evidenced by both low levels of backside radiation and a pronounced minimum in the scattering parameter spectrum.

[0068] Degrees of freedom provided by the phases of the input port signals enable various interference patterns to be synthesized, including those with spatially shifted focal regions. Software control of these phases can refocus the fields without mechanical reconfiguration, which can be useful for implanted devices inserted on rhythmic organs or for locomotive devices. In some embodiments, a “greedy” phase search algorithm can be implemented based on closed-loop feedback that obtains focusing-enhanced power transfer in real-time. In other embodiments, the feedback signal can be wirelessly transmitted from the implanted device to the midfield source.

[0069] FIGS. 1C and 1F show a patch sub-wavelength structure 102c, disposed over a substrate 104 with a ground plane 106 on a bottom surface of the substrate. A feed 108 is also shown in Fig. 1F, which is used to feed or transmit electrical signals to or from the sub-wavelength structure. FIGS. 1D and 1G illustrate a PIFA sub-wavelength structure 102d,

disposed over a substrate 104 with a ground plane 106 on a bottom surface of the substrate. The feed 108 is shown in FIG. 1G, along with a short 110 connected to the structure 102d. FIGS. 1E and 1H show a slot sub-wavelength structure 102e in a ground plane 106 disposed over a substrate 104. The feed 108 is shown in FIG. 1H. FIGS. 1I and 1L show a cross slot sub-wavelength structure 102i in a ground plane 106 disposed over a substrate 104. The feed 108 is shown in FIG. 1L. FIGS. 1J and 1M illustrate an aperture coupled circular slot sub-wavelength structure 102j in a ground plane 106 disposed over a substrate 104. This embodiment can further include a ground plane 106 on a bottom surface of the substrate. The feed 108 is shown in FIG. 1M. Finally, FIGS. 1K and 1N illustrate a half slot sub-wavelength structure 102k, disposed over a substrate 104 with a ground plane 106 on a top surface of the substrate. The feed 108 is shown in FIG. 1N. In all the embodiments described above and illustrated, one or more power source(s) and amplifier(s) can be connected to the sub-wavelength structure(s) via the feeds (or ports) to manipulate evanescent fields. Furthermore, in some embodiments, each sub-wavelength structure can include one or more feeds or ports.

15 [0070] The wireless power transmitting modules 100 described above generally include one or more sub-wavelength structures, one or more excitation ports, a substrate, and one or more ground planes. The modules 100 can be controlled by a controller (both hardware and software) to dynamically shift a focal region of the electromagnetic field.

20 [0071] Some discussion on various techniques for transferring wireless power will now be described. FIG. 2 shows the magnetic field 212 generated by a conventional inductively coupled loop source 214, in both the yz and xz planes. As can be seen, the magnetic field is generated perpendicular to the tissue interface 216, and is parallel with the direction of desired wireless power transfer to an implant disposed in tissue below the loop source, such as an implanted device 218.

25 [0072] In contrast, FIGS. 3A-3E show the magnetic fields 312 produced by various sub-wavelength structures of the present disclosure. These structures generate a magnetic field 312 parallel to the tissue interface 316, and perpendicular to a propagating wave generated in tissue that transmits wireless power to an implanted device 318. FIG. 3A shows the magnetic field generated with a patch sub-wavelength structure 302c (FIGS. 1C and 1F) in the yz and xz planes. FIG. 3B shows the magnetic field generated with a PIFA sub-wavelength structure 302d (FIGS. 1D and 1G) in the yz and xz planes. FIG. 3C shows the magnetic field generated with a cross slot sub-wavelength structure 302i (FIGS. 1I and 1L) in the yz and xz planes. FIG. 3D shows the magnetic field generated with an aperture coupled circular slot structure 302j (FIGS. 1J and 1M) in the yz and xz planes. FIG. 3E shows the magnetic field generated with a half slot sub-wavelength structure 302k (FIGS. 1K and 1N) in the yz and xz planes.

[0073] FIG. 4A shows a wireless power transmitting system including a wireless power transmitting module 400 and an implanted device 418 inside a human body. In Fig. 4A, the device is shown implanted in a chest cavity of the patient, such as in or near the heart. It should be understood from this figure that the implanted device can be placed anywhere in the body, such as in the heart, brain, lungs, spinal cord, bones, nerves, sinuses, nasal cavity, mouth, ears, peritoneal cavity, arms, legs, stomach, intestines, digestive tract, kidneys, bladder, urinary tract, or any other organ or part of the body that can benefit from the sensing and/or stimulation features provided by the systems described herein.

[0074] In FIG. 4A, the transmitting module 400 can be positioned above the skin of the patient, and the implanted module comprising a receive coil can be implanted in the patient. Power transfer occurs when the interaction of the source fields with the coil structure results in work extruded by a load in the implanted module. For a sub-wavelength coil, only the lowest order mode is important and the transfer mechanism can be described by electromagnetic induction characteristics of dynamic magnetic field interactions. The electric and magnetic fields generated by a time-harmonic current density J_S on the surface of the source conductor can be solved by decomposing the current density into its spatial frequency components. Each component corresponds to a plane wave with propagation determined by phase matching conditions for refraction and reflection over planar boundaries, from which the total field in tissue can be recovered at each depth z by integration over the source spectrum.

[0075] The properties of the mid-field region are key to optimal powering. The sub-wavelength structures manipulate evanescent fields to excite/control propagating waves (alternating electric and magnetic fields) and thereby generate a spatially focusing and adaptive steering field/signal in tissue that converges on the implanted device. Back-propagation of fields at the focal plane to the surface of the skin reveals that the source is highly oscillatory and composed of significant evanescent components that are important only in the near-field. In contrast with conventional near-field powering, however, these evanescent components excite propagating modes in tissue that transport energy to absorption-limited depths.

[0076] FIGS. 4B-4C show the difference between the ability of a near-field or inductively coupled wireless power transfer system (FIG. 4B) to transfer power into a depth of tissue compared to the mid-field design (FIG. 4C) of the present disclosure. As seen in FIG. 4C, the mid-field design of the present disclosure allows for transmission of wireless power to a depth in tissue not attainable by inductively coupled systems.

[0077] In some embodiments, a focal point of the wireless power transfer system of the present disclosure can be adjusted to change a direction of the propagating wave. FIG. 4C illustrates formation of a propagating wave in a direction directly below the external module,

along line 419a. However, in some embodiments, the focal point can be adjusted to cause the propagating wave to travel in a steer direction through the tissue, such as along lines 419b or 419c. This adjustment can be attained by adjusting a phase and/or amplitude of one or more of the sub-wavelength structures of the external module.

5 [0078] FIGS. 5A-5B shows two embodiments of architectures for a controller of the wireless power transmitting modules described herein, for exciting the ports of the sub-wavelength structures. These architectures can be configured to control one or more sub-wavelength structures 502a-502n of the wireless power transmitting modules. In each architecture, the RF signal can be sourced from an oscillator 520, and be divided symmetrically into multiple RF signals through a power divider. In the architecture of FIG. 5A, the signal is then fed through attenuator(s) 522 with variable controllable attenuation settings. The signals can then be fed through phase shifter(s) 524 with controllable phase, and then amplified with amplifier(s) 526. This architecture produces controlled phase and amplitude signals at each port of the module. The architecture on in FIG. 5B is configured to produce the same controlled phase and amplitude signals, but with fewer components by combining the amplifier(s) and the amplitude control element(s) into a single component 528.

10 [0079] **Implanted module.** One embodiment of an implanted module for receiving wireless power is shown in FIG. 6. The implanted module can include a coil 630 disposed over an integrated chipset (IC) 632. The coil 630 can be a loop (or multiple loops) of a conductor. In some embodiments, the coil 630 has a diameter of less than 2mm. The coil can be configured to receive the wireless power transmitted from the external modules described herein. The module can optionally include features 634 for sensing and/or stimulating tissue, such as electrode(s) or sensors. The electrodes can comprise, for example, screw-type electrodes, planar electrodes, or cuff electrodes. In other embodiments, the sensors can comprise biopotential sensors, pressure sensors, O₂ sensors, etc. The implanted module can optionally include electrical components for the storage of energy, such as a capacitor or battery 636. Due to the small size of the implanted module (2mm or less in diameter), the implanted module can be delivered and implanted into a patient with minimally invasive techniques, such as with a catheter 638, a cannula, a needle, or the like.

15 [0080] Because the power levels supported by a midfield wireless powering approach far exceed requirements for microelectronic technologies (e.g., in one embodiment, an input power level of 500mW from the external module can deliver approximately 200uW of power over 5cm of tissue to a 2mm diameter implant coil), more sophisticated functions can be implemented such as real-time monitoring of chronic disease states or closed-loop biological sensing and control by

the implanted module. Hence, in some embodiments, the implanted module can include one or more of the following building blocks:

[0081] *Power management.* To increase the efficiency of rectification and power management of wirelessly powered implants operating in the electromagnetically weakly

5 coupled regime, AC-DC conversion circuits in the implanted module can be divided into the low-voltage and high-voltage domains. FIG. 7A shows an architecture that can be included in the IC of the implanted module to handle the power management features of the implant. FIG. 7A shows a coil 730 electrically connected to one or more capacitors (or variable capacitors) 740, multistage rectifiers 742, and regulators 744, to divide the AC-DC conversion circuits into 10 low-voltage and high-voltage domains.

[0082] *Battery storage.* A rechargeable battery such as thin film battery can be included in the implanted module for temporary energy storage and for use as an efficient charge pump for the power management circuitry. In some embodiments, the thin film battery can be stacked to increase the energy density.

15 **[0083]** *Power detection.* The instantaneous power level received by the implanted module can be detected and sent via a data transmitter to the external module for adaptive focusing onto the implant module in the midfield. Data can be transmitted between the implanted module and the external module through a wireless link. In some embodiments, the wireless link can operate in the frequency range of the power transmission, or in other embodiments, the wireless link can 20 operate in a different frequency range. The detected power level can be used in a closed-loop feedback control with the controller of the system to adjust and focus the external module for optimal wireless power transfer.

25 **[0084]** *Pulsed RF modulation.* Conventional load modulation does not work in the midfield due to the low quality factor of the implant antenna, leading to poor signal-to-noise ratio and substantial link margin fluctuation. To overcome this problem, the data transmitter of the implanted module can use pulsed RF modulation. To ease detection at the external module, the data and power carriers can operate at different center frequencies.

30 **[0085]** *Programmable current drivers.* Stimulation applications differ mainly by the characteristics of the electrical pulses such as intensity, duration, frequency, and shape. The current drivers for stimulation are designed to support wide range of these parameters and can be programmed via the wireless data link. The current drivers can also be configured to support actuation such as locomotion.

[0086] *Programmable digital core.* The digital core coordinates the interaction among various blocks in the implanted module, communication between the implant and external

modules, and the multi-access protocols. Each implant module can have its own identification (ID) such as via an ID stored in the memory of the implanted module.

[0087] *Data receiver and transmitter.* The external module can remotely communicate with each implanted module to program or configure each implanted module via the data receiver.

5 FIG. 7B shows one embodiment of a data receiver based on envelop detection and a data transmitter based on an ultra-wideband architecture. The receiver and transmitter can be time multiplexed by a T/R switch 746 connecting to the power receiving coil or to a separate antenna. Each implanted module can have its own ID 748 for multi-access. A digital controller 750 can be implemented to handle the multi-access protocol 752, commands from the external module, 10 and feedback data to the external module.

[0088] *Sensing frontend.* The sensing frontend can comprise pre-amplifiers, analog-to-digital converters (ADC) to discretize signals from the pre-amplifiers, and drivers for the sensors. Signals from the output of the ADCs can either be stored in the non-volatile memory of the implanted module or sent to the external module via the Pulsed RF modulator. In addition, 15 the sensed signals can provide biological feedback for adjusting parameters of the current drivers. FIG. 7C shows the architecture for one or multiple LED drivers, and the electrical sensing and stimulation frontends. The LED drivers can be connected to LEDs for optical stimulation of tissue (nerves). The electrical sensing and stimulation frontends can also be connected to electrodes for sensing the biological activities and altering the electrical pathways.

20 **[0089]** *Non-volatile memory.* Flash memory, for example, can be included to record usage model of the implant module such as the time of activation and setting of the current deriver, and/or to store measurements from the sensing frontend.

[0090] *Modular construction.* The implanted module can be customizable depending on the particular needs or requirements of the end user. For example, the implanted module can include 25 a number of base components including the wireless power receiving coil and the IC, and can further include an interface that can receive any type of sensor or stimulator desired by the user. For example, the implanted module can be configured to receive any type of sensor, such as thermal, chemical, pressure, oxygen, PH, flow, electrical, strain, magnetic, light, or image sensors, or any type of stimulator, such as electrical, optical, chemical, or mechanical 30 stimulators, or a drug delivery apparatus. The modular approach of the implanted module can therefore be customized to accommodate the particular needs of the user.

[0091] All the above building blocks in the implanted module can be integrated into a single die as system-on-chip (SoC) or multiple dies enclosed in a single module as system-in-package (SiP).

[0092] **External module.** The external module (described above) can be configured to energize and control the implanted modules, and to perform noninvasive readout through a bidirectional wireless link setup with the implanted modules. The external module can include one or more of the following building blocks:

5 [0093] *Midfield coupler.* FIGS. 1A-1N show various shapes and patterns for the external module or midfield coupler, which can include one or more sub-wavelength structures. The coupler can be made on solid substrate, or on a flexible substrate configured to conform to the skin surface of patients.

10 [0094] *Dynamic midfield focusing circuits and algorithms.* Based on the power measurement feedback from the implant module, the external module can run an algorithm, for example, the greedy search algorithm, to change the phase and/or magnitude settings in each element of the midfield coupler so as to dynamically shift the focal region to the individual implant module. For example, the implanted module can detect a power level of received wireless energy, and the external module can automatically adjust the phase and/or amplitude of 15 the sub-wavelength structures to adjust the focal point of the transmitted energy signal. This adjustment can be made automatically and in real time to optimize wireless power transmission between the external module to the internal module.

20 [0095] *Bidirectional wireless link to the implant module.* The wireless link can activate the implanted module, program the setting of the implanted module, and download measurements from the sensing frontend of the implanted module. The data rate for the downlink; from the external module to the implanted module, can be a few Mbps or lower, while the data rate for the uplink; from the implant module to the external module should be higher, can be in the range of 10's Mbps or even higher.

25 [0096] *Multiaccess protocols.* These protocols can coordinate the implanted modules to carry out synchronous tasks such as coordinated multi-site stimulation. In some embodiments, multi-access schemes can be time multiplexing and frequency multiplexing.

30 [0097] *Patient/clinician user interface.* A peripheral device including a display can be integrated with the external module to interface with a patient and/or clinician. In other embodiments, the integrated peripheral device can be replaced by a bidirectional wireless link communicating with a smartphone or a tablet. In this embodiment, the patient and clinician can interface with the external module using the display of the smartphone or tablet through the wireless link.

35 [0098] In some embodiments, the entire external module can be integrated into a palm-size device and held by the patient for on-demand applications. It can also be worn on the body or affixed to the skin surface. Patients can use the external module to charge the battery of the

implant modules as needed. In some embodiments, the implanted module(s) can be charged with only a few minutes of wireless charging per week/month. During charging, patients can also download usage record from the implant modules and send the record to the clinician for analyses.

5 [0099] Various aspects of the present disclosure are directed toward powering of multiple active implantable sensors or devices using a single power source. The types of implantable devices/sensors that can be powered using the single power source, consistent with various aspects of the present disclosure, are numerous. For instance, the implantable devices can be used for muscular stimulation, stimulation/sensing to regulate a patient's heart beat, multisite 10 deep brain stimulation, drug delivery, and/or biological, physiological, and chemical sensing. The systems described herein can also be configured to be used in the following applications:

15 [0100] **Cardio pacemaker.** The implanted module can be delivered via a catheter through the vasculature into the right ventricle of a patient. A separate implanted module can be delivered through the coronary sinus into the coronary vein, and placed on the left ventricular epicardium. These implanted modules can include stimulation and sensing electrodes to apply leadless pacing to the heart. Thus, leadless biventricular pacing can be achieved with the present system with only minimally invasive procedures. In addition, the procedure time can be shortened substantially over prior approaches. This can also eliminate any complication during to the multiple leads and extensions.

20 [0101] **Deep-brain stimulation.** Current procedure involves the drilling of holes with diameter > 1 cm in the skull to insert a lead and the extension from the lead to the stimulating module. Due to the invasiveness of the procedure, only a limited number of target sites are selected for placing the electrodes. By contrast, the implanted modules in this disclosure, being very small, can be injected into the brain via other less invasive routes. Since there is no lead 25 and extension wire in the present system, more target sites for stimulation can be supported. This results in less infection and lower regulatory risk.

30 [0102] **Spinal cord stimulation.** Batteries in newer models of spinal cord stimulator are rechargeable due to the high power requirement. However, their powering approaches are exclusively based on inductive coupling (or near-field coupling). Since the harvesting components are large in these systems, they can only be placed subcutaneously. Therefore, the lead and extension wires in these systems potentially restrict the location of the electrodes for effective stimulation. In this disclosure, the power-harvesting component in the implanted module is relatively tiny. The entire implanted module can be easily placed next to the targeted nerve region in the spinal cord and requires no lead wire connecting them. This results in less 35 infection, less damage to the spinal cord tissue, and more effective stimulation.

[0103] **Peripheral nerve stimulation.** Most current devices support low-frequency stimulation and only a few of them support high-frequency low-intensity stimulation due to the much higher power requirement. The systems of this disclosure can support both modes. In addition, the bidirectional wireless link provides instant programmability, switching between 5 different modes.

[0104] **Stimulation to treat obstructive sleep apnea (OSA).** The implanted modules of this disclosure can be injected and directly embedded into the muscular tissue near the tongue, and can deliver electrical stimulation to open the airway of a patient during sleep. Multiple implant modules can be injected into different muscular groups to intensify the muscle 10 contraction. When needed, patients can charge the implanted modules with the external module and simultaneously, download a time stamp of each OSA episode. This information can be sent to the clinicians. Data collected can also be used to reprogram the implanted modules.

[0105] **Medical sensors.** Batteryless implanted sensors are typically passive in nature, that is, there is no active circuitry in the device to condition the sensed signals. To compensate for 15 the poor signal quality, an external reader is needed to be very sophisticated and is usually large (cannot be fitted on a palm). In addition, not many stimuli can be detected by passive sensors. The lack of active implanted sensors is mainly due to the lack of an efficient wireless powering approach. For example, the inductive coupling approach used in the rechargeable impulse generator for spinal cord stimulation has limited penetration and the receiver (the implanted 20 device) is large. The system of the present disclosure allows for the transfer of substantial amount of power to small implanted modules at nearly any location in the body from a palm-size external module. This enables an array of new sensing applications for continuous monitoring in the medical field, for example, post-surgery oxygen sensing in the heart and the brain.

[0106] **Wireless endoscopes.** Current capsule endoscope has limited battery lifetime, 25 leading to incomplete small-bowel examination which is one of the major clinical failures. The implant module in our invention is small and has indefinite power supply, solving the deficiency of current endoscopes. In addition, since our implant module is many times smaller than the current capsule endoscope, patients can swallow multiple of the implant modules simultaneously. They are expected to orient differently in the intestine and therefore, can take 30 pictures from different angles at the same location, improving the field of view. The images collected from them will improve the diagnosis. Finally, the probability of retention is expected to be dramatically reduced, avoiding the need of surgical or endoscopic retrieval.

[0107] **Implanted drug delivery.** Current implanted drug delivery systems are large and mostly cannot be placed local to the site that the drug is needed. Based on this disclosure, the 35 implanted module can be injected into a targeted tissue region (for example, a tumor) where the

drug is needed. The implanted module can include a number of drug reservoirs. The drug reservoirs can be activated by the external module via the patient/clinician user interface to release a drug into the targeted tissue region.

[0108] **Temporary treatment.** Currently, screening tests are typically performed before a permanent impulse generator is implanted. During the screening test, a patient may receive a temporary, external impulse generator. The generator can connect to an extension and a lead that are surgically placed in the body. In this period, the external impulse generator collects patient usage data and efficacy of the treatment. However, according to this disclosure, the implanted module having an electrode and an impulse generator can be injected into the targeted nerve/muscle region, eliminating the need for a temporary generator with leads. There is therefore no need for the external temporary impulse generator. In addition, this disclosure can also replace the temporary sensing and pacing leads used in patients after cardiac surgery.

[0109] **Laboratory Experiments.** The implanted module can be injected into lab animals or rodents (such as mice, rats, etc.) to monitor or sense parameters of the animal and/or provide stimulation to the animal in an experimental setting. The small size of the implanted module can advantageously provide opportunities to monitor the animal that has not been previously available. For example, the implanted module could be implanted on or near the brain of a rodent to monitor electrical signals of the brain. The implant can be wirelessly powered with the external module described above, and can be configured to communicate information back to the external module relating to the animal.

[0110] The devices are individually addressable and independently controlled. Thus, the devices, for example as those used for muscular stimulation, can be placed at different locations corresponding to different muscle groups, and perform stimulation in a synchronized manner.

[0111] Similarly, brain stimulation devices can be placed at different locations in the brain, and stimulation can be performed in a synchronized manner. The same can be said with drug delivery devices. Moreover, because the devices can be individually addressable and independently controlled, the devices can be activated and/or powered asynchronously as well as synchronously. These devices, in certain instances, can have characteristics dimensions in that the devices are much smaller (*e.g.*, one, two, or three orders of magnitude) than their depth in tissue. Similarly, the devices, in certain instances, can have characteristics dimensions in that the devices are much smaller (*e.g.*, one, two, or three orders of magnitude) than the source that provides the power to the devices.

[0112] The aspects of the present disclosure, as directed toward apparatuses, devices, and methods, can be utilized alone or in combination with various other aspects.

[0113] For information regarding details of other embodiments, experiments and applications that can be combined in varying degrees with the teachings herein, reference may be made to the experimental teachings and underlying references provided in the following attachments which form a part of this patent document and are fully incorporated herein by reference. Embodiments discussed in these appendices are not intended, in any way, to be limiting to the overall technical disclosure, or to any part of the claimed disclosure unless specifically noted.

[0114] In such contexts, these building blocks and/or modules represent circuits that carry out one or more of these or other related operations/activities. For example, in certain embodiments discussed above, one or more blocks and/or modules are discrete logic circuits or programmable logic circuits configured and arranged for implementing these operations/activities, as in the circuit modules/blocks described above and in the Appendices. In certain embodiments, the programmable circuit is one or more computer circuits programmed to execute a set (or sets) of instructions (and/or configuration data). The instructions (and/or configuration data) can be in the form of firmware or software stored in, and accessible from, a memory (circuit).

[0115] In connection with the above discussed features and illustrative figures, such structures can be used with sensors/devices that include feedback to the sub-wavelength structures. These types of sensors can include, for example, implantable temperature sensors or imaging devices.

[0116] In this manner, the devices are responsive to the structures illustrated above that generate a spatially adaptable electromagnetic field/signal. The feedback-type devices respond to the power and/or data portions of the signal provided by the spatially adaptable electromagnetic field/signal, and are prompted to respond. For instance, temperature sensors located in a patient will broadcast/report the temperature of the tissue in response to the power and/or data portions of the signal provided by the spatially adaptable electromagnetic field/signal. Additionally, imaging devices implanted in a tissue can broadcast/report the captured images in response to the power and/or data portions of the signal provided by the spatially adaptable electromagnetic field/signal. Moreover, the penetration depth of the spatially adaptable electromagnetic field/signal can be modeled and controlled. Thus, in certain embodiments, the feedback devices can indicate and label data, in response to the spatially adaptable electromagnetic field/signal, to record the depth at which the device is operating. By storing this data on a patient-by-patient basis in a storage device, a computer can access and analyze this data for statistical purposes.

[0117] By storing the position or label of the feedback-type device in a memory circuit via a programmable computer, various patient feedback tracking methods can also be realized. For

instance, the depth of an implantable imaging device can be optimized by analyzing the surrounding tissue. In this manner, the depth of the implantable imaging device can be adjusted if it is determined that a more optimal position is possible. Similarly, the depth of an implantable stimulation device can be used to determine the health of the tissue area surrounding the stimulation device, and determine an optimal positioning of the device in response to the spatially adaptable electromagnetic field/signal. Additionally, the feedback-type devices can respond to the spatially adaptable electromagnetic field/signal and broadcast data stored in a memory circuit. Thus, the feedback-type devices can continuously update a physician of the data that is being tracked by the device. This allows for real-time monitoring, diagnosing, and/or treating a patient wirelessly.

[0118] While the present disclosure (which includes the attachments) is amenable to various modifications and alternative forms, specifics thereof have been shown by way of example in the drawings and will be described in further detail. It should be understood that the intention is not to limit the disclosure to the particular embodiments and/or applications described. Various embodiments described above and shown in the figures and attachments may be implemented together and/or in other manners. One or more of the items depicted in the drawings/figures can also be implemented in a more separated or integrated manner, as is useful in accordance with particular applications.

[0119] As for additional details pertinent to the present invention, materials and manufacturing techniques may be employed as within the level of those with skill in the relevant art. The same may hold true with respect to method-based aspects of the invention in terms of additional acts commonly or logically employed. Also, it is contemplated that any optional feature of the inventive variations described may be set forth and claimed independently, or in combination with any one or more of the features described herein. Likewise, reference to a singular item, includes the possibility that there are plural of the same items present. More specifically, as used herein and in the appended claims, the singular forms "a," "and," "said," and "the" include plural referents unless the context clearly dictates otherwise. It is further noted that the claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as "solely," "only" and the like in connection with the recitation of claim elements, or use of a "negative" limitation. Unless defined otherwise herein, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. The breadth of the present invention is not to be limited by the subject specification, but rather only by the plain meaning of the claim terms employed.

CLAIMS

The claims defining the invention are as follows:

1. A wireless power system, comprising:

an external module having one or more sub-wavelength structures configured to transmit wireless power by manipulating evanescent fields outside of tissue to generate propagating fields inside the patient's tissue and thereby generate a spatially focused field in tissue; and

an implantable module configured to receive the wireless power from the external module, the implantable module including at least one sensor configured to sense a parameter of the tissue or at least one stimulator configured to apply stimulation to the tissue.

2. The system of claim 1 wherein the at least one sensor is selected from the group consisting of a thermal sensor, a chemical sensor, a pressure sensor, and oxygen sensor, a PH sensor, a flow sensor, an electrical sensor, a strain sensor, a magnetic sensor, and an imaging sensor.

3. The system of claim 1 wherein the at least one stimulator is selected from the group consisting of an electrical stimulator, an optical stimulator, a chemical stimulator, and a mechanical stimulator.

4. The system of claim 1 wherein the implantable device comprises a modular design that allows interchangeable sensors and/or stimulators.

5. The system of claim 1 wherein the one or more sub-wavelength structures are selected from the group consisting of a patch, a PIFA, a slot in a ground plane, a cross slot in a ground plane, an aperture coupled circular slot in a ground plane, and a half slot in a ground plane.

6. The system of claim 1 wherein the external module further comprises:
one or more excitation ports coupled to the one or more sub-wavelength structures; at least one voltage source coupled to the one or more excitation ports; and
a controller configured to adjust a phase and/or an amplitude delivered to the one or more sub-wavelength structures to adjust a position of a focal point of the spatially focused field in the tissue.
7. The system of claim 6 wherein the controller is configured to detect a power level of received wireless energy from the implanted module, and is configured to provide feedback to automatically adjust the position of the focal point to optimize wireless power transmission.
8. The system of claim 1 wherein the implantable module is configured to be implanted on, in, or near a heart to apply leadless pacing to the heart.
9. The system of claim 1 wherein the implantable module is configured to be implanted on, in, or near a brain to apply deep brain stimulation to the brain.
10. The system of claim 1 wherein the implantable module is configured to be implanted on, in, or near a spinal cord to apply stimulation to the spinal cord.
11. The system of claim 1 wherein the implantable module is configured to be implanted on, in, or near a muscular tissue of the tongue to apply stimulation to the tongue to treat obstructive sleep apnea.
12. A method of providing therapy to a patient, comprising:
implanting a wireless power receiving module in the patient;
generating propagating fields inside the patient's tissue to transmit a mid-field propagating wave to the wireless power receiving module to power the module;

sensing a parameter of the patient with the wireless power receiving module; and providing a therapy to the patient with the wireless power receiving module based on the sensed parameter.

13. The method of claim 12 wherein the generating step further comprises manipulating evanescent fields outside of the patient's tissue to generate the propagating fields inside the patient's tissue and thereby generate a spatially focused field in the tissue.

14. A method of cardiac pacing in a patient, comprising:
implanting a wireless power receiving module in, on, or near a heart;
generating propagating fields inside the patient's tissue to transmit a mid-field propagating wave to the wireless power receiving module to power the module;
sensing a parameter of the heart with the wireless power receiving module; and
providing electrical pacing to the heart with the wireless power receiving module based on the sensed parameter.

15. The method of claim 14 wherein the generating step further comprises manipulating evanescent fields outside of the patient's tissue to generate the propagating fields inside the patient's tissue and thereby generate a spatially focused field in the tissue.

16. A method of deep brain stimulation of a patient, comprising:
implanting a wireless power receiving module in, on, or near a brain;
generating propagating fields inside the patient's tissue to transmit a mid-field propagating wave to the wireless power receiving module to power the module;
sensing a parameter of the brain with the wireless power receiving module; and
providing stimulation to the brain with the wireless power receiving module based on sensed parameter.

17. The method of claim 16 wherein the generating step further comprises manipulating evanescent fields outside of the patient's tissue to generate the propagating fields inside the patient's tissue and thereby generate a spatially focused field in the tissue.

18. A method of stimulating tissue, comprising:
 - implanting a wireless power receiving module into tissue;
 - generating propagating fields inside the tissue to transmit a mid-field propagating wave to the wireless power receiving module to power the module;
 - sensing a parameter of the tissue with the wireless power receiving module; and
 - providing stimulation to the tissue with the wireless power receiving module based on sensed parameter.
19. The method of claim 18 wherein the generating step further comprises manipulating evanescent fields outside of the tissue to generate the propagating fields inside the tissue and thereby generate a spatially focused field in the tissue.
20. The method of claim 18 further comprising adjusting a focal point of the propagating wave to optimize wireless power transmission to the module.
21. The method of claim 18 wherein the transmitting step comprises transmitting the wave with a sub-wavelength structure that produces a magnetic field perpendicular to the wave and parallel to a tissue interface.
22. An apparatus configured to transfer wireless power through tissue, comprising:
 - a substrate;
 - at least one sub-wavelength structure disposed on the substrate;
 - at least one radio-frequency port coupled to the at least one sub-wavelength structure;
 - a voltage or current source coupled to the at least one radio-frequency port; and
 - a controller configured to manage excitation of the at least one radio-frequency port and sub-wavelength structure with the voltage or current source to manipulate evanescent fields outside of tissue to generate propagating fields inside the tissue and thereby generate a spatially focused field in the tissue.

23. The apparatus of claim 22, wherein each of the at least one sub-wavelength structure is coupled to a respective independent radio-frequency port.

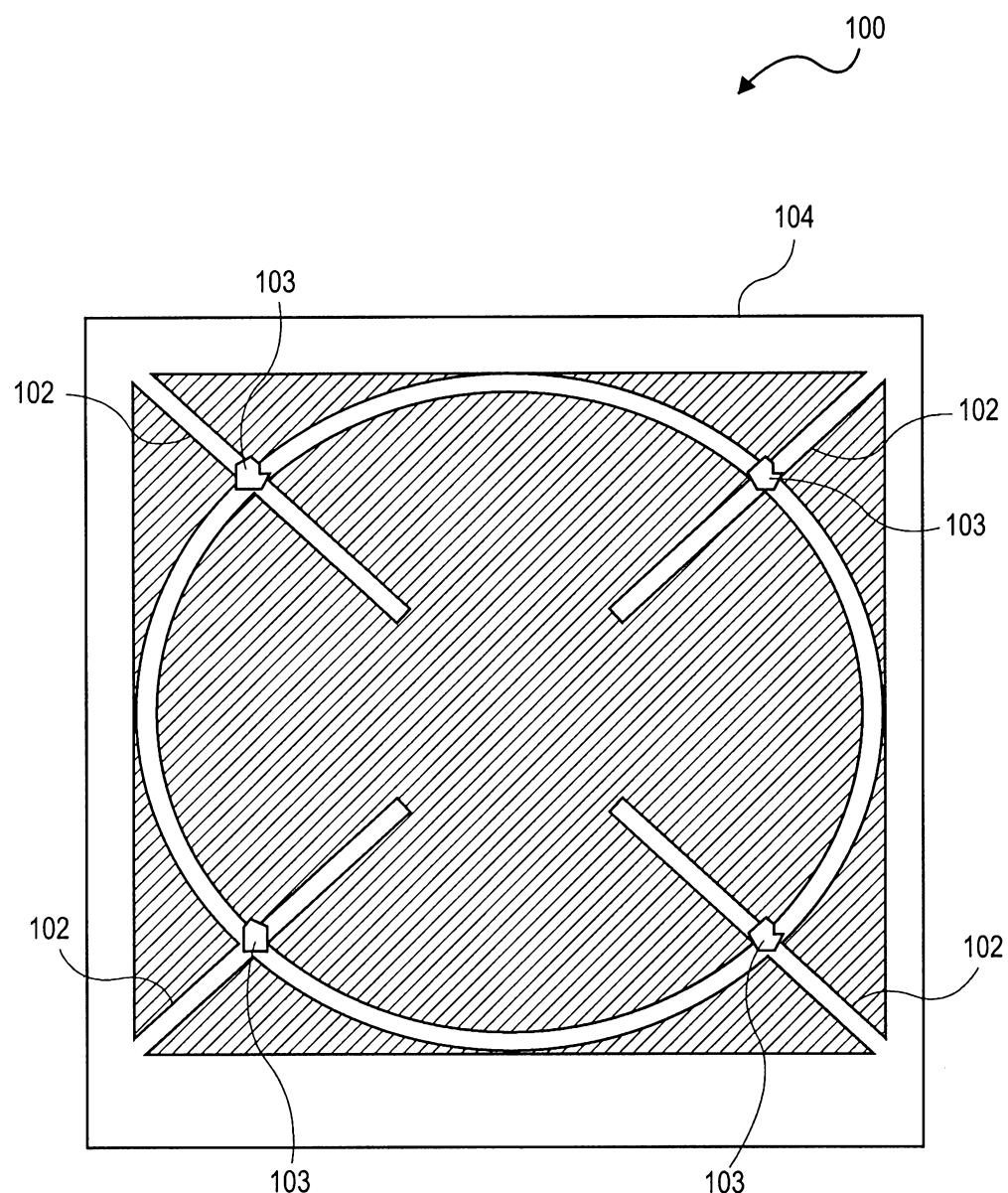
24. An apparatus configured to transfer wireless power through tissue, comprising:
a plurality of sub-wavelength structures configured and arranged to generate propagating fields inside tissue and thereby generate a spatially adaptable electromagnetic field in the tissue;

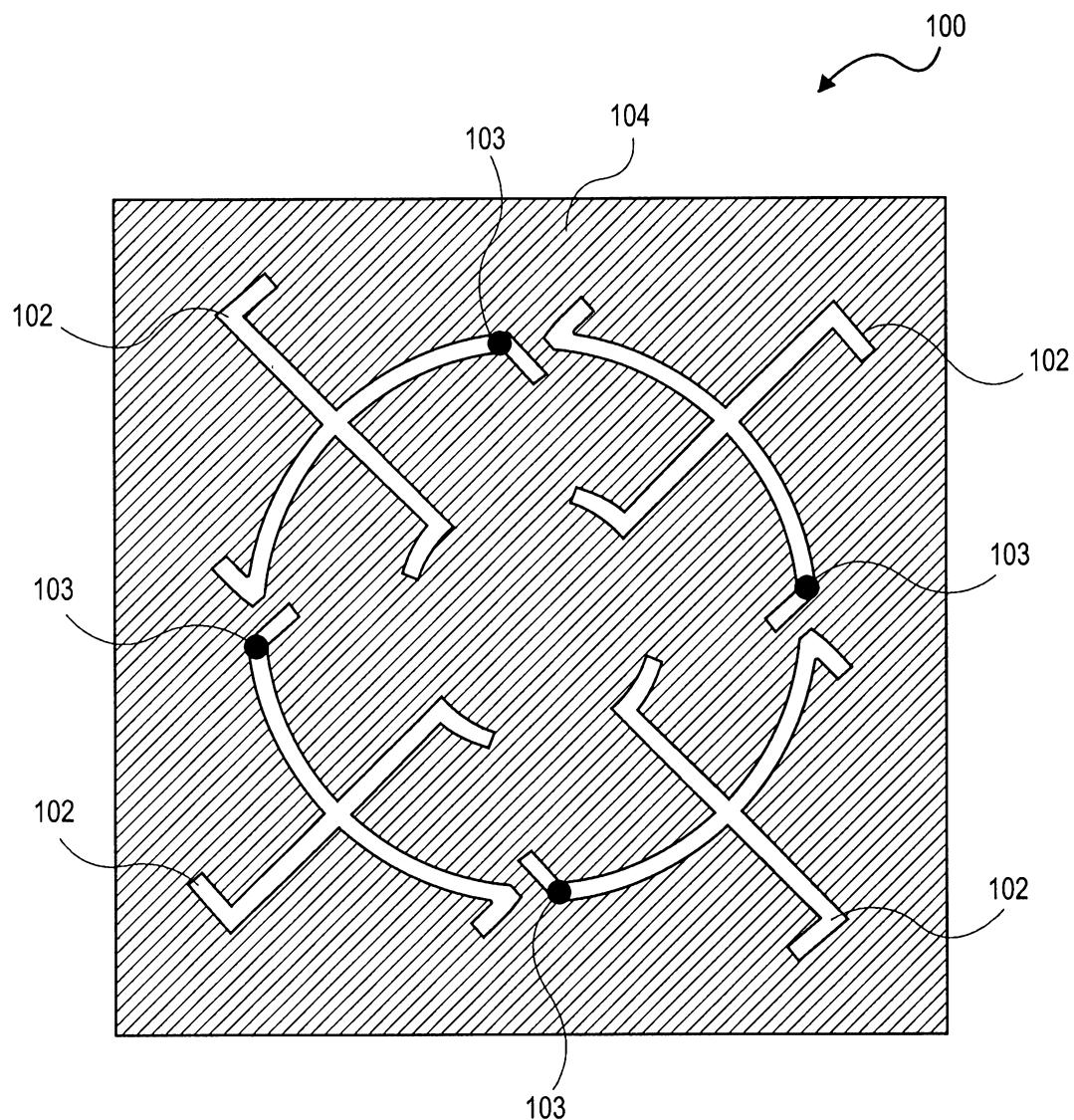
a plurality of independent feed ports configured and arranged to individually excite a respective one of the plurality of sub-wavelength structures thereby generating the spatially adaptable electromagnetic field; and

a controller configured to redistribute a peak surface electromagnetic field to increase an allowable radio frequency output power.

25. The apparatus of claim 24, wherein the plurality of sub-wavelength structures are further configured and arranged to generate an adaptive steering field in tissue.

26. The apparatus of claim 24, wherein the spatially focusing and adaptive steering field/signal has a frequency between 300 MHz and 3000 MHz.

**FIG. 1A**

**FIG. 1B**

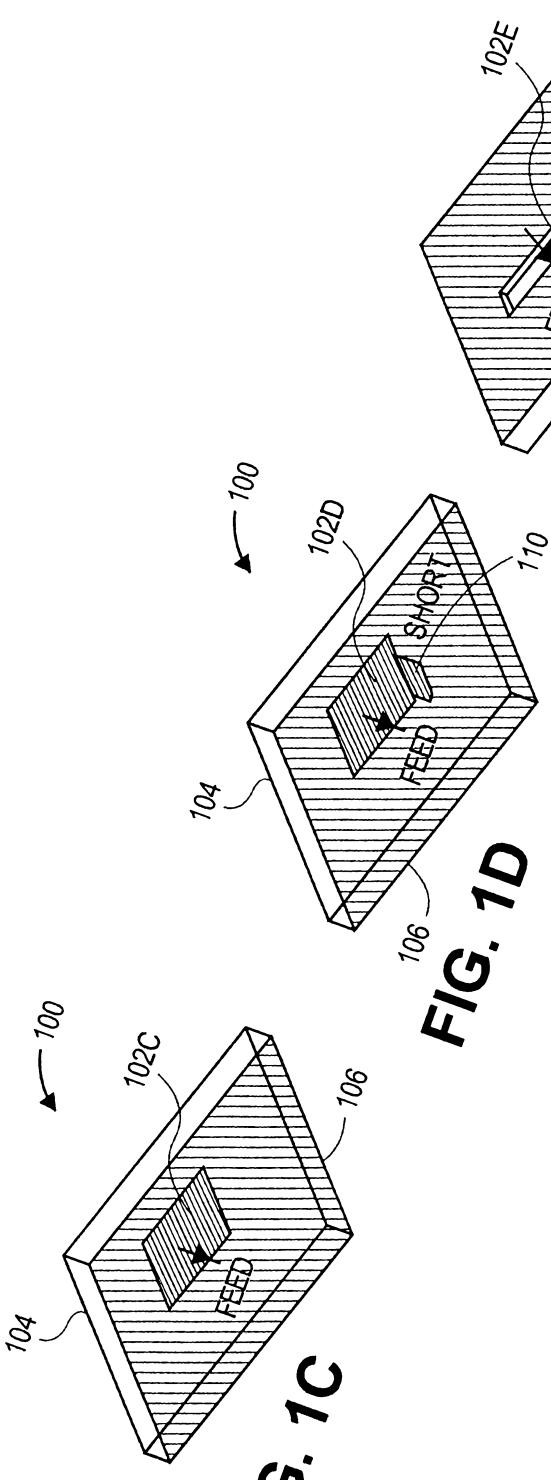


FIG. 1C

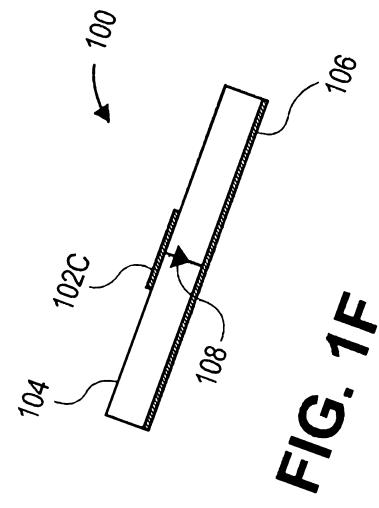


FIG. 1F

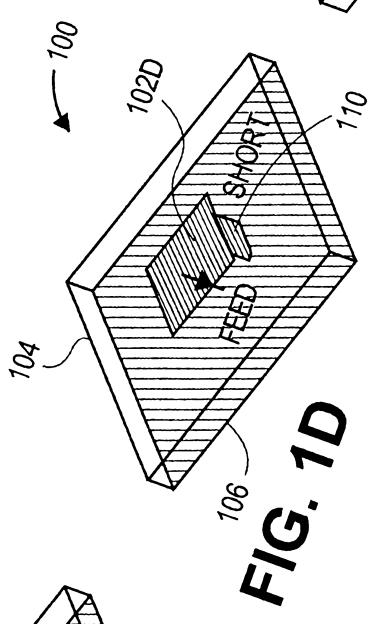


FIG. 1D

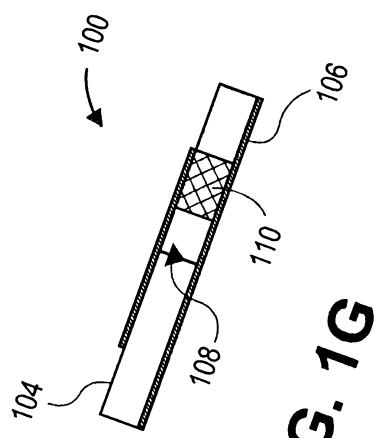


FIG. 1G

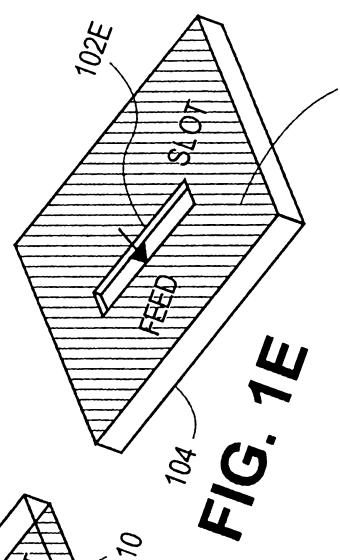


FIG. 1E

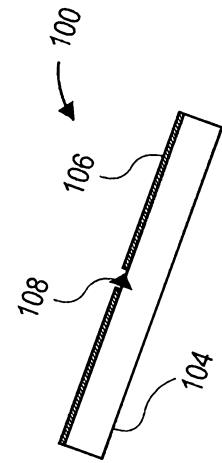
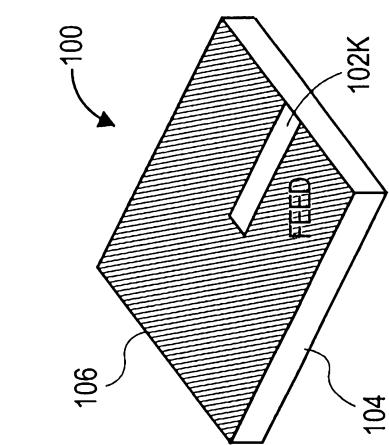
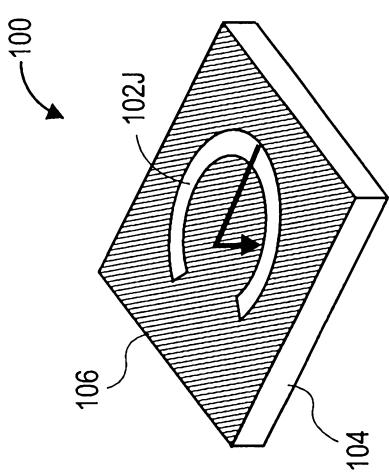
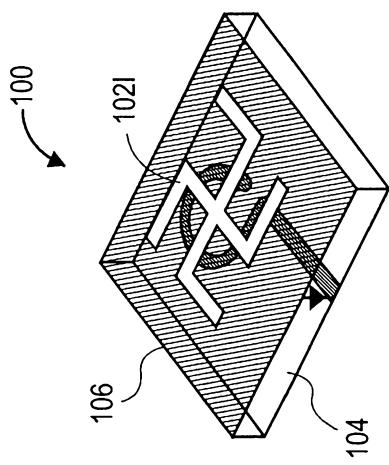
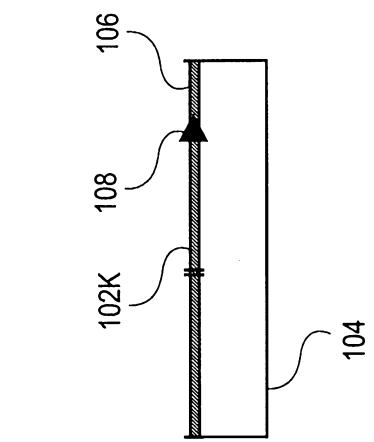
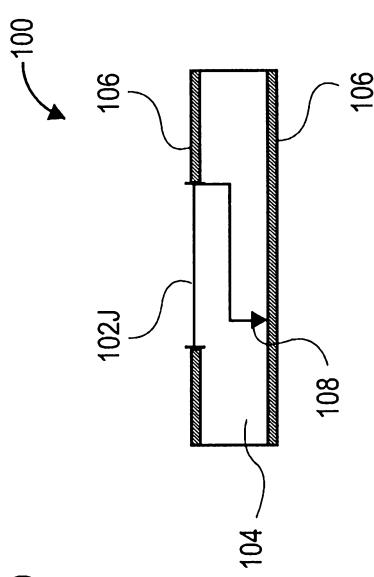
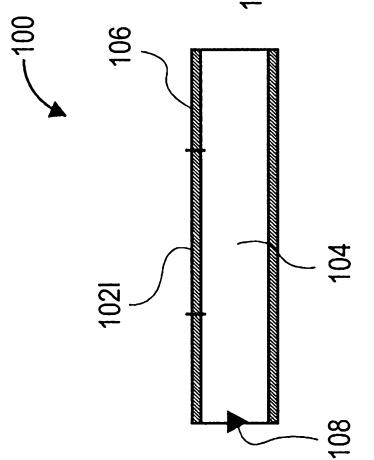


FIG. 1H

**FIG. 1K****FIG. 1J****FIG. 1I****FIG. 1N****FIG. 1M****FIG. 1L**

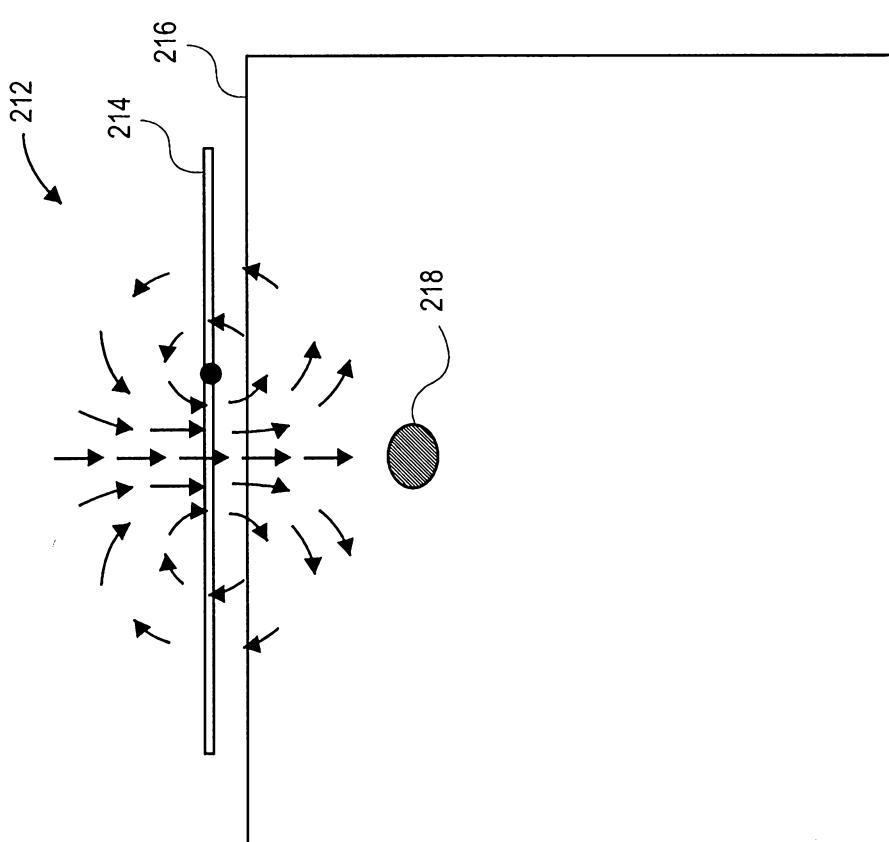
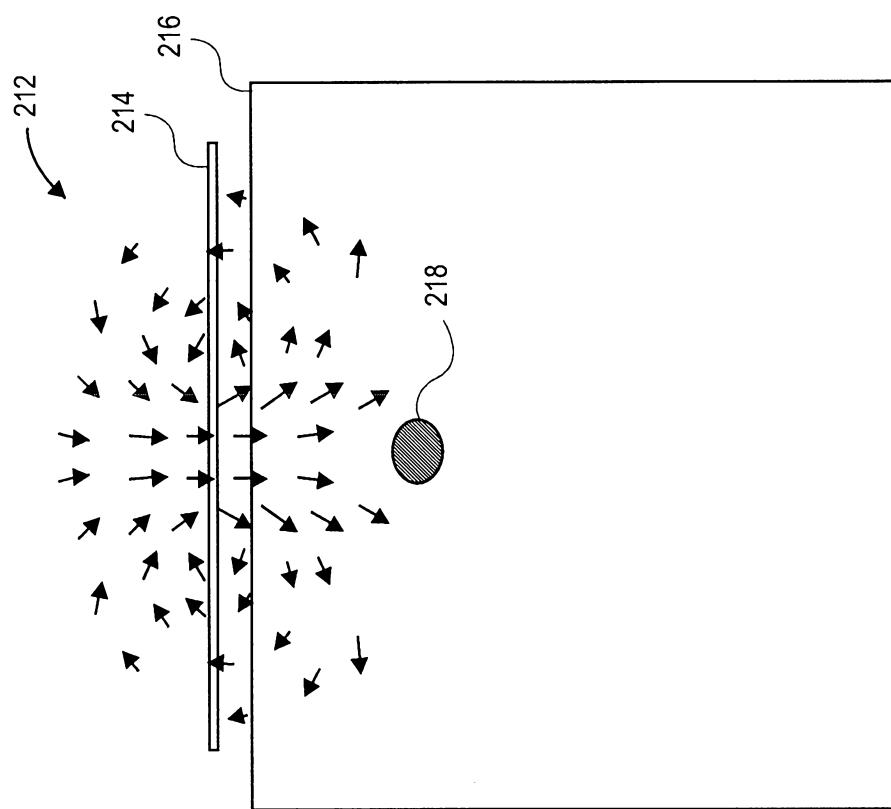


FIG. 2

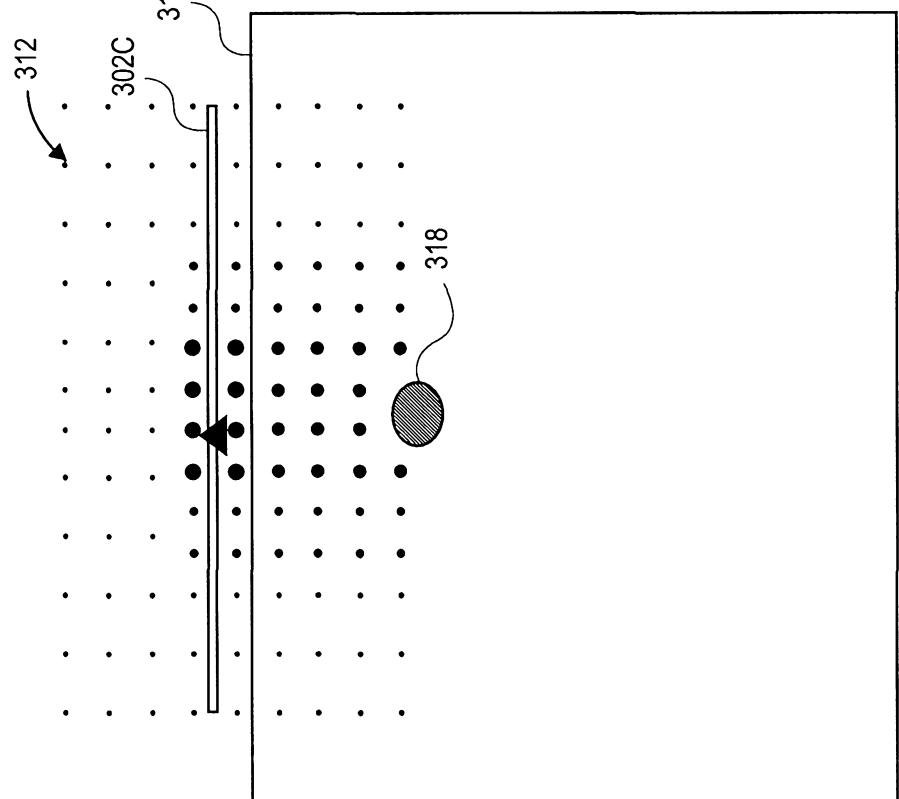
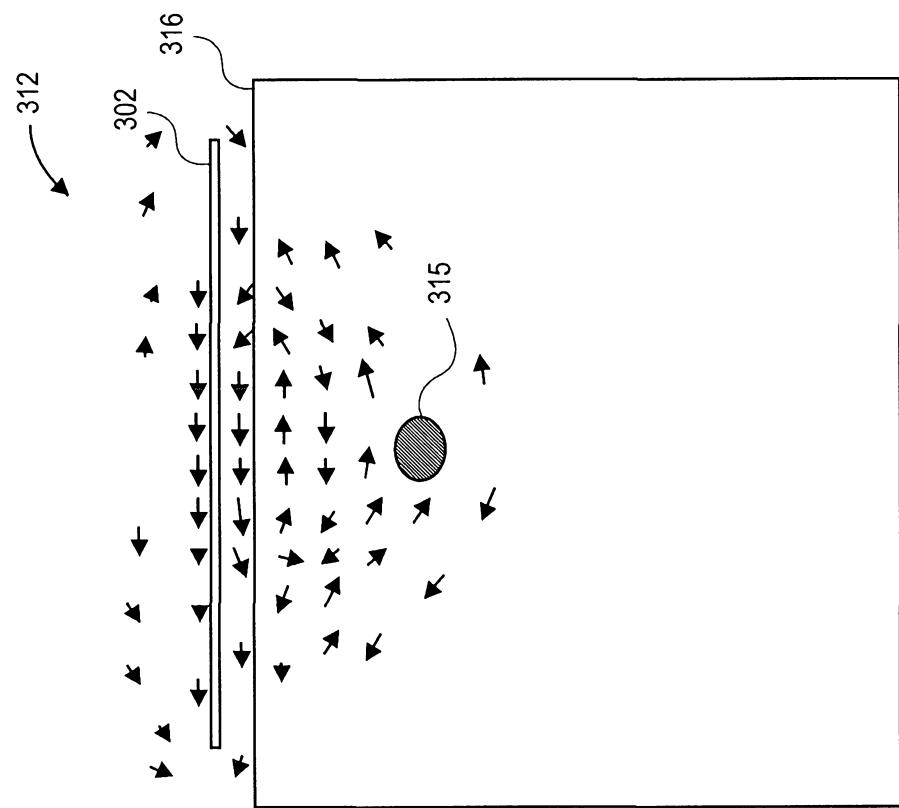
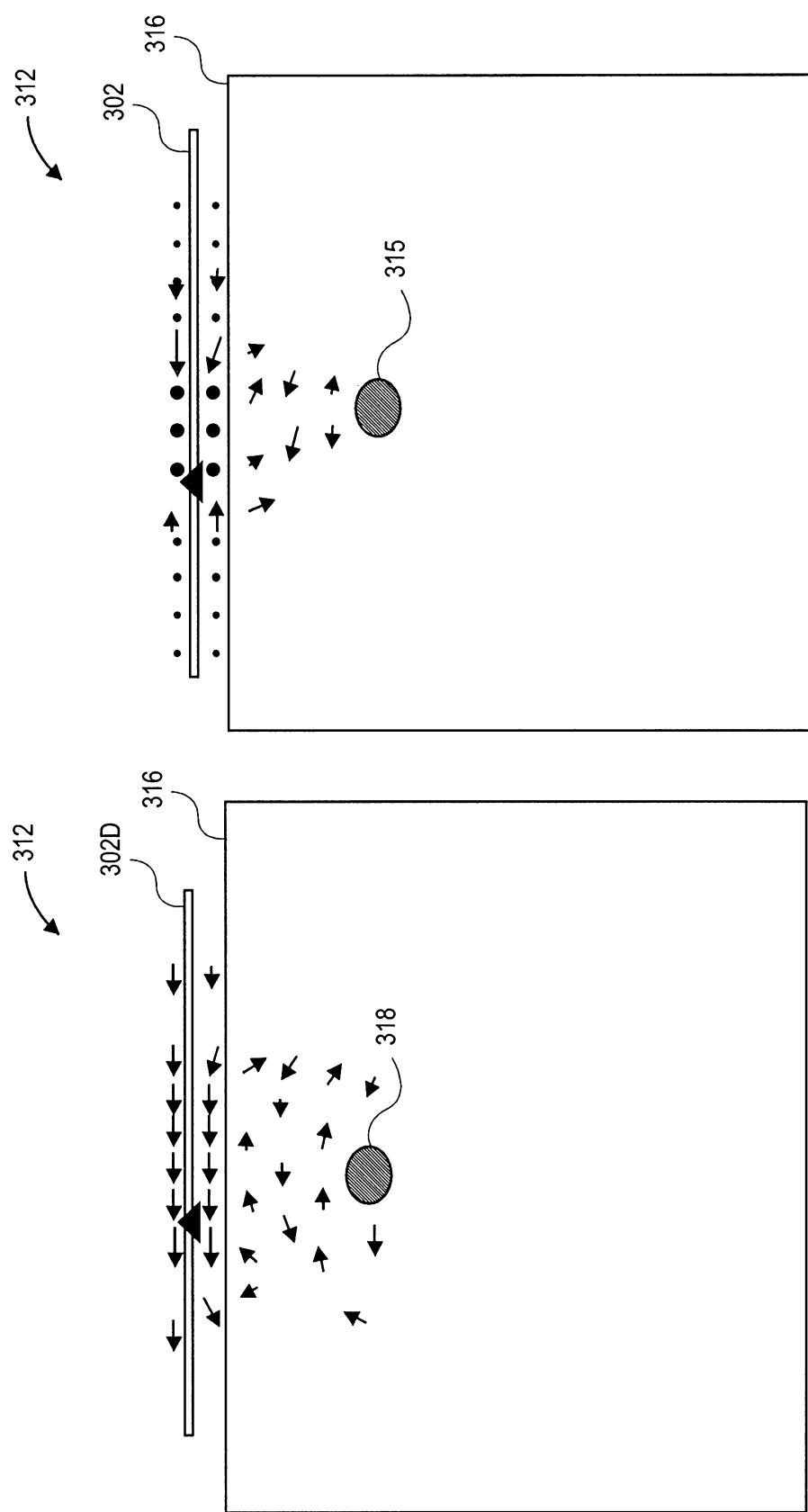


FIG. 3A

**FIG. 3B**

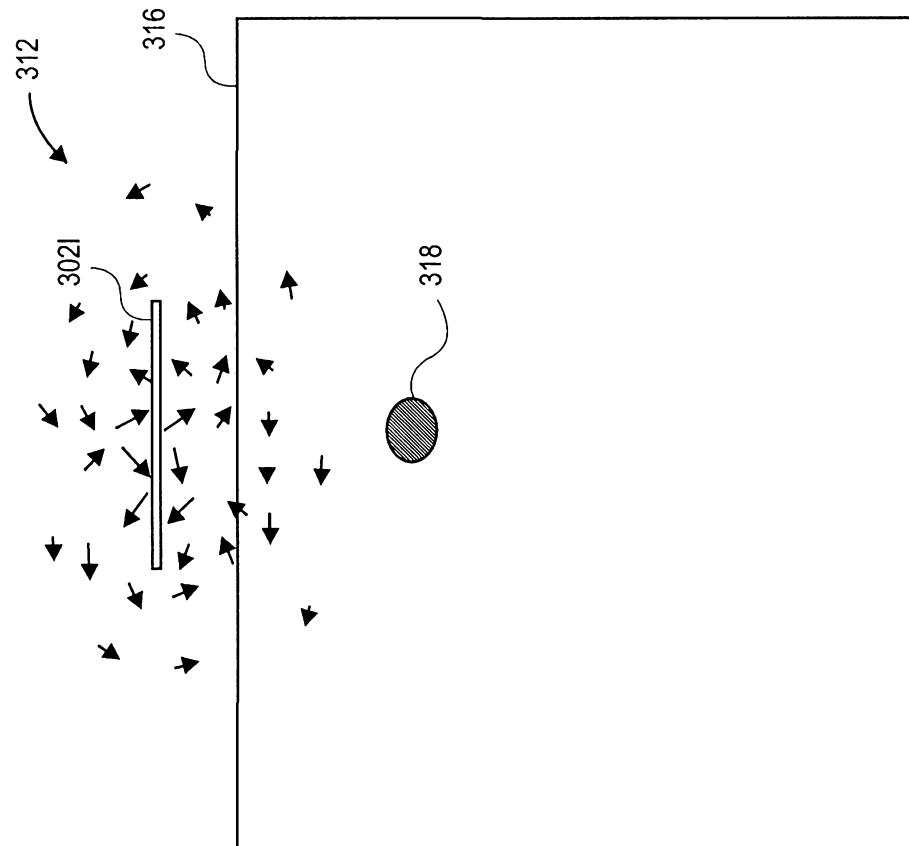
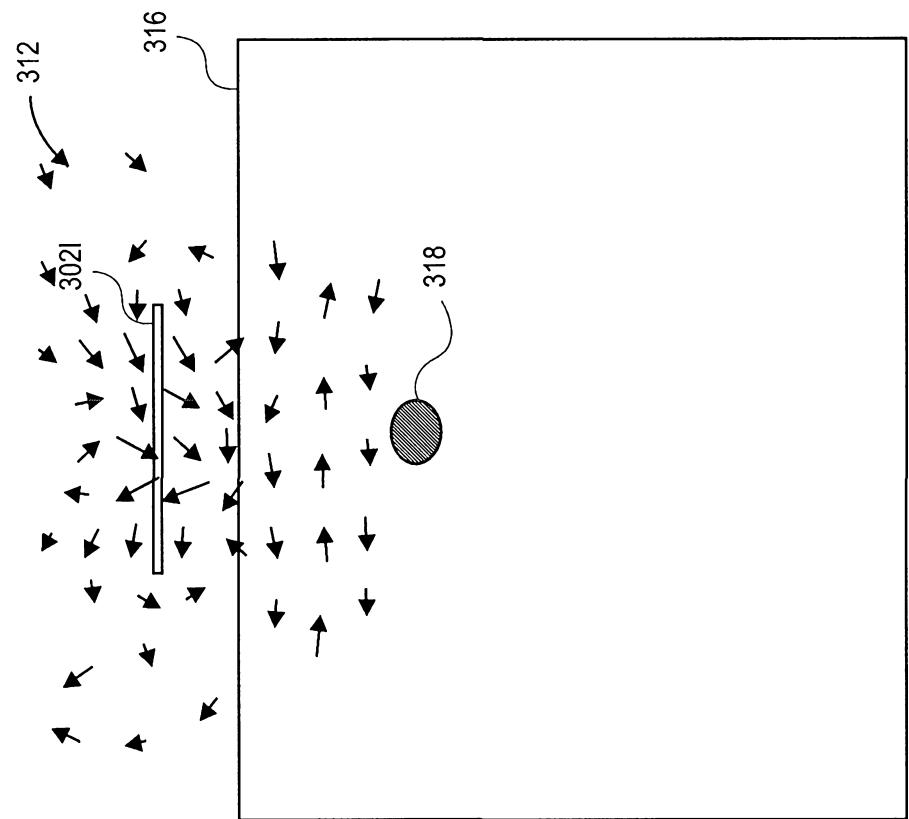
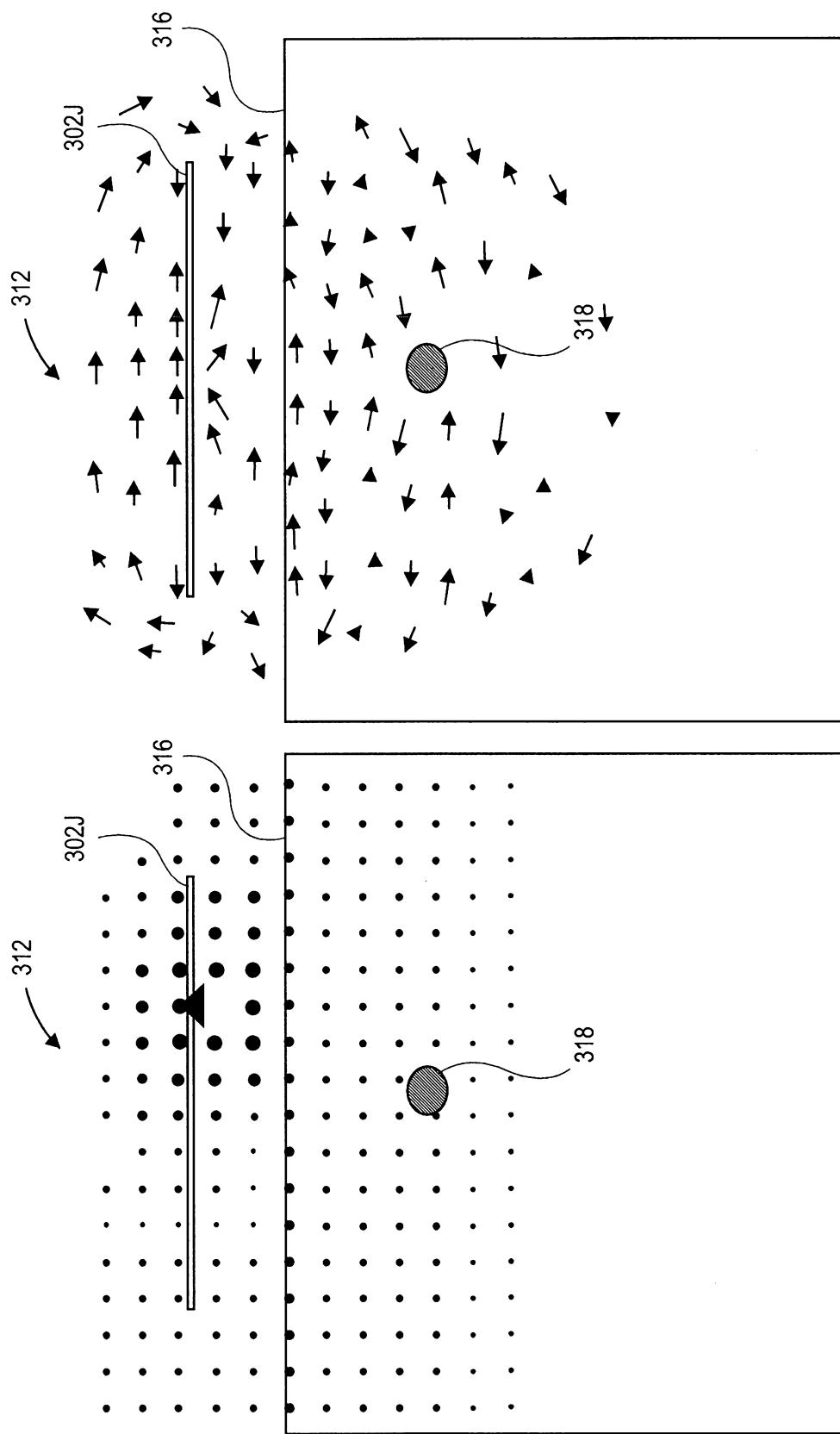


FIG. 3C

**FIG. 3D**

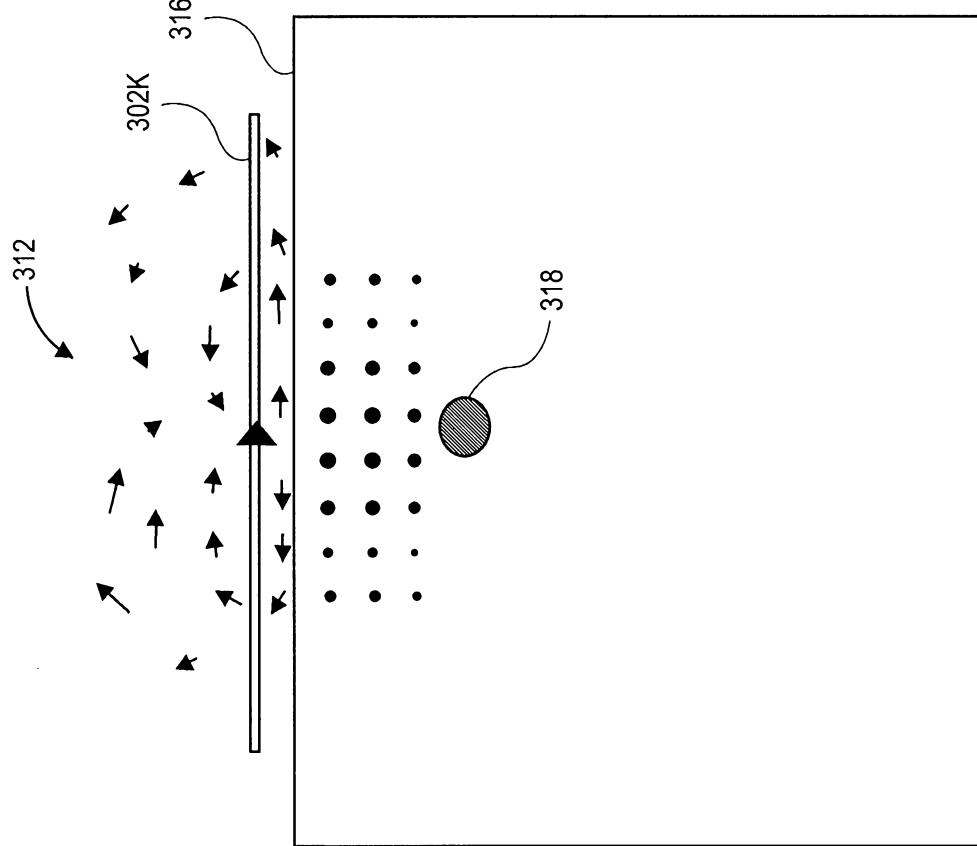
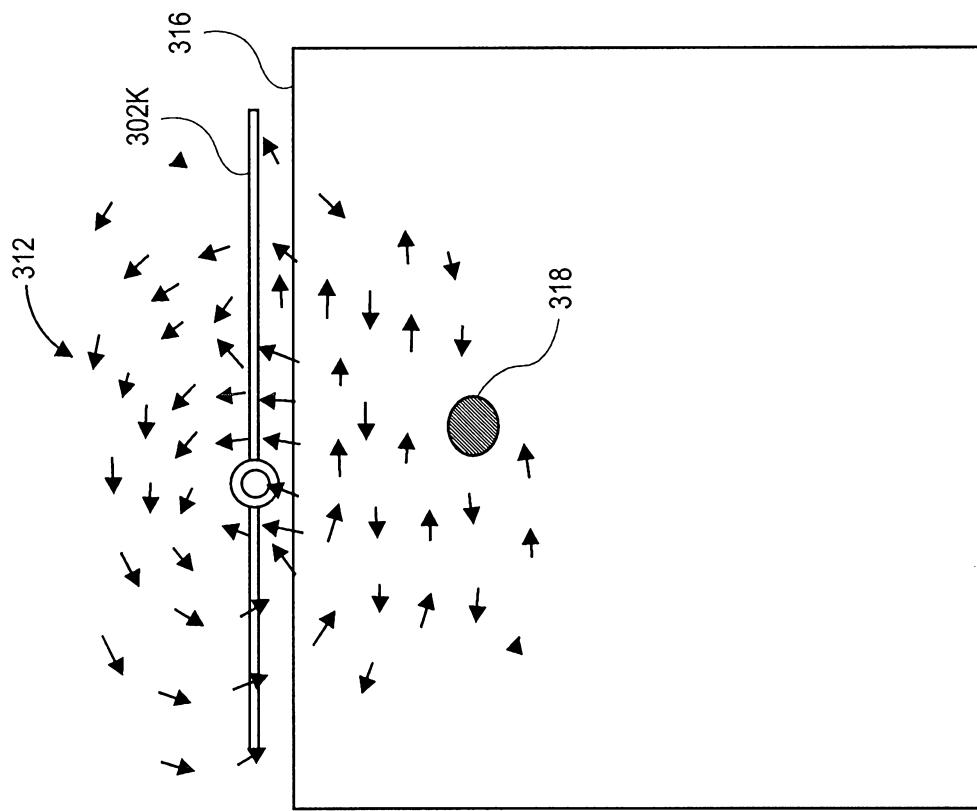
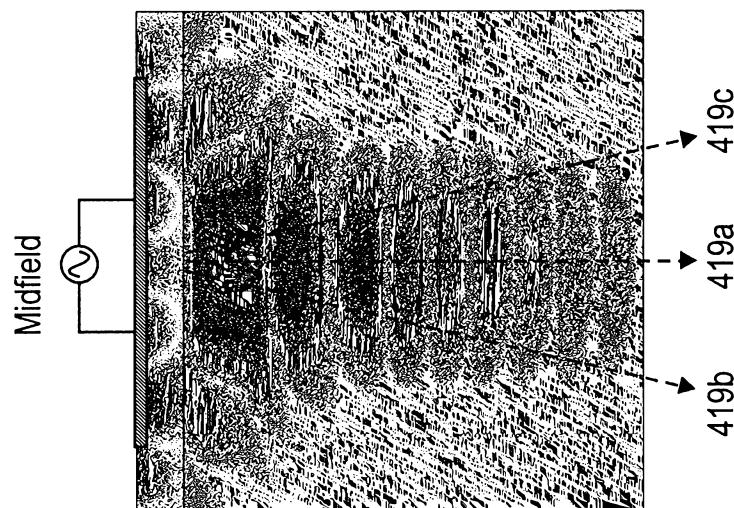
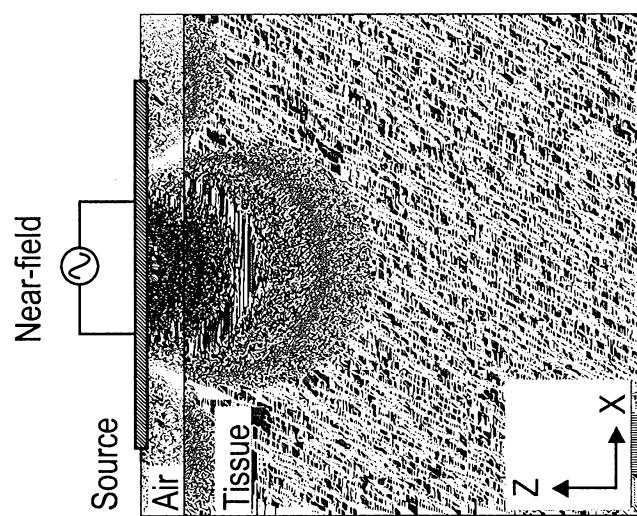
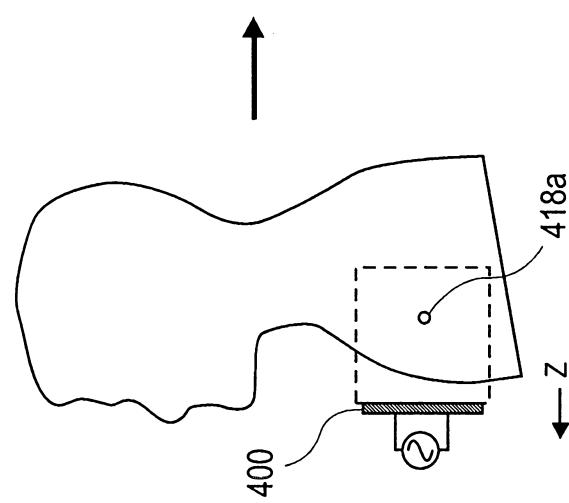


FIG. 3E

**FIG. 4C****FIG. 4B****FIG. 4A**

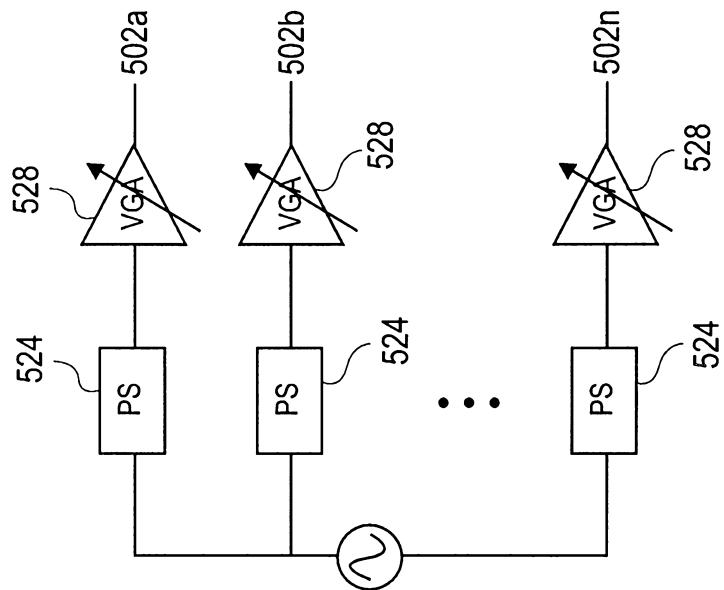


FIG. 5B

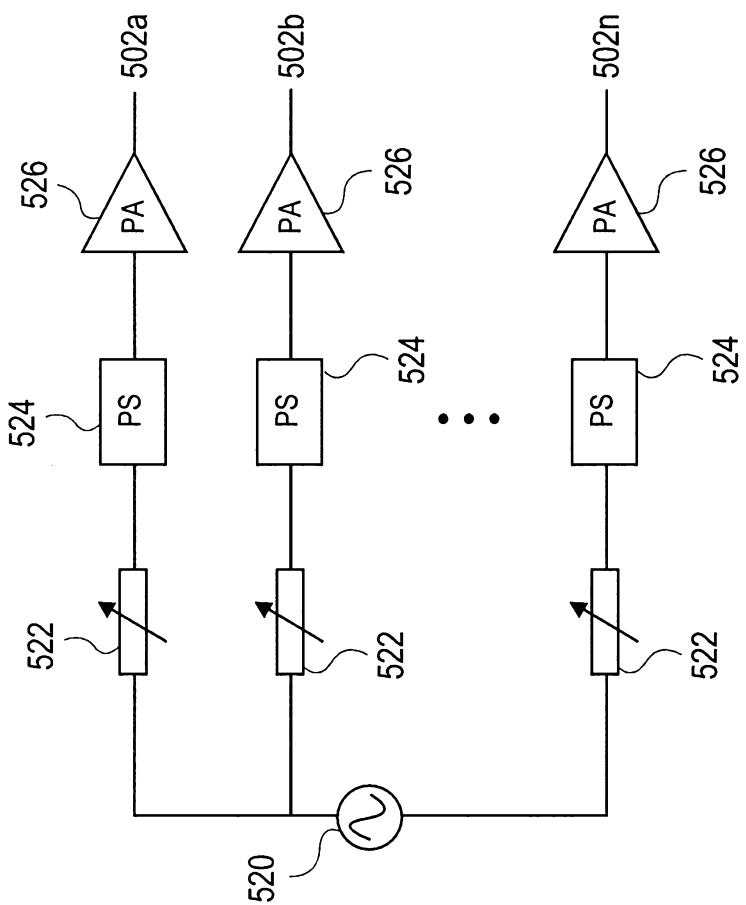
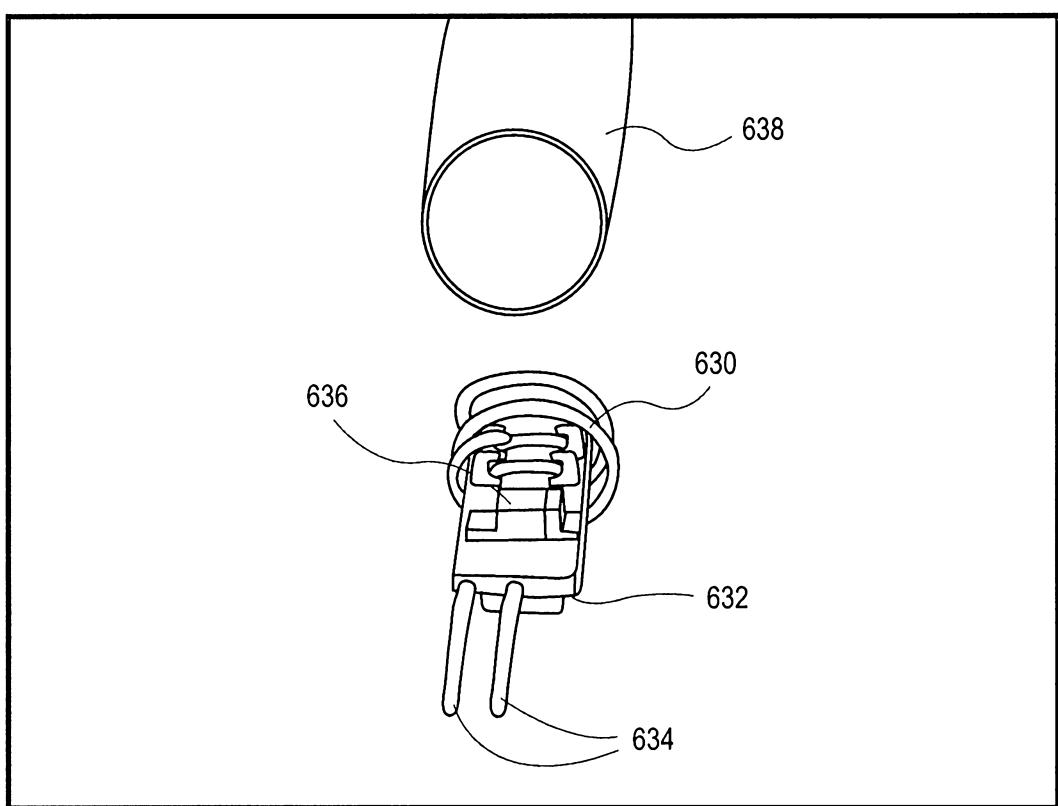
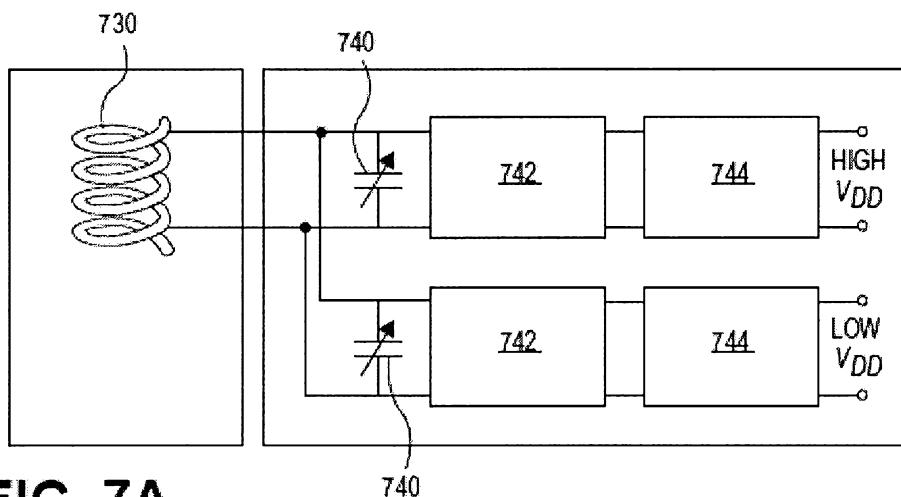
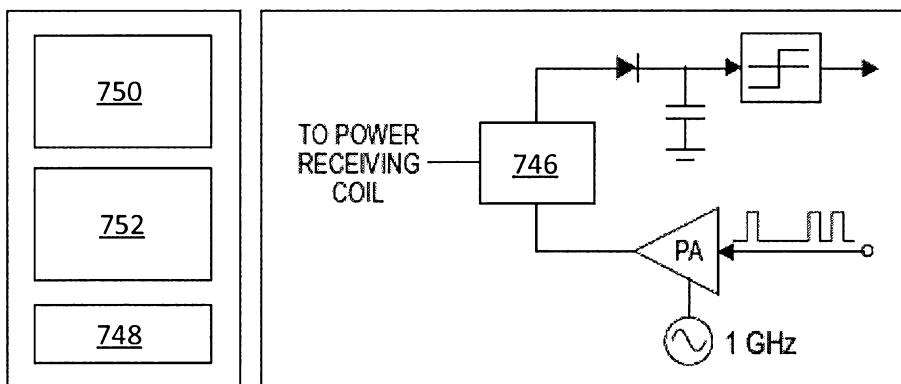
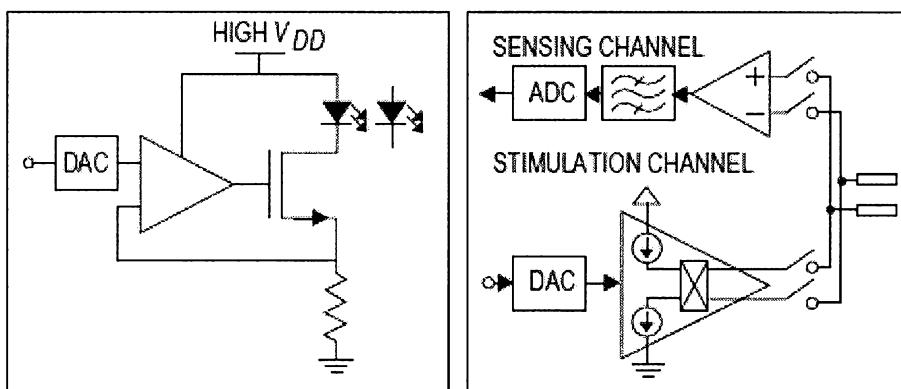


FIG. 5A

**FIG. 6**

**FIG. 7A****FIG. 7B****FIG. 7C**