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[Continued on next page]

(54) **Title**: MULTI-SENSOR COMPRESSIVE IMAGING

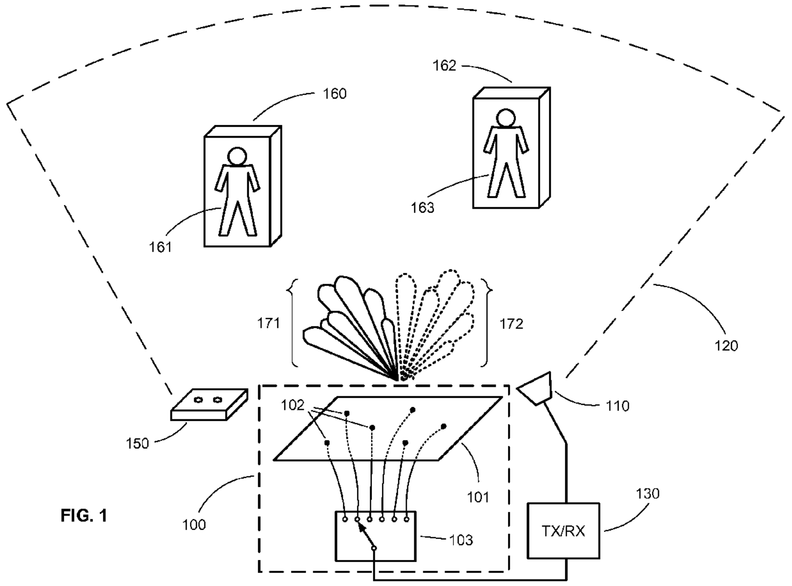

FIG. 1

(57) **Abstract**: Multi-sensor compressive imaging systems can include an imaging component (such an an RF, microwave, or mmW metamaterial surface antenna) and an auxialiary sensing component (such as an EO/IR sensor). In some approaches, the auxiliary sensing component includes a structured light sensor configured to identify the location or posture of an imaging target within a field of view of the imaging component. In some approaches, a reconstructed RF, microwave, or mmW image may be combined with a visual image of a region of interest to provide a multi-spectral representation of the region of interest.

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Multi-Sensor Compressive Imaging

Inventor(s): David Brady, Tom Driscoll, John Hunt, Daniel Marks, Alexander Mrozack, Matthew Reynolds, David R. Smith

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is related to United States Patent Application No. **13/891,165**, entitled **METAMATERIAL DEVICES AND METHODS OF USING THE SAME,** naming **DAVID BRADY, TOM DRISCOLL, JOHN HUNT, DANIEL MARKS, ALEXANDER MROZACK, MATTHEW REYNOLDS, DAVID R. SMITH** as inventors, filed **MAY 9, 2013** and later published as United States Patent Application Publication No. **2013/0335256**, which claims priority to United States Provisional Patent Application No. **61/644,736**, entitled **METAMATERIAL DEVICES AND METHODS OF USING THE SAME**, naming **DAVID R. SMITH, DAVID BRADY, TOM DRISCOLL, JACK HUNT, ALEXANDER MROZACK, MATTHEW REYNOLDS,** and **DANIEL MARKS** as inventors, filed **MAY 9, 2012**, and to United States Provisional Patent Application No. **61/753,584**, entitled **METAMATERIAL DEVICES AND METHODS OF USING THE SAME**, naming **DAVID R. SMITH, DAVID BRADY, TOM DRISCOLL, JACK HUNT, ALEXANDER MROZACK, MATTHEW REYNOLDS,** and **DANIEL MARKS** as inventors, filed **JANUARY 17, 2013**; the entire contents of which are hereby incorporated by reference in their entireties.

[0002] This application is related to PCT Application No. **PCT/US13/40444**, entitled **METAMATERIAL DEVICES AND METHODS OF USING THE SAME,** naming **DAVID BRADY, TOM DRISCOLL, JOHN HUNT, DANIEL MARKS, ALEXANDER MROZACK, MATTHEW REYNOLDS, DAVID R. SMITH** as inventors, filed **MAY 9, 2013** and later published as PCT Publication No. **WO/2014/025425**, the entire content of which is hereby incorporated by reference in its entirety.

[0003] The present application claims benefit of priority of United States Provisional Patent Application No. **61/890,043**, entitled **MULTI-SENSOR COMPRESSIVE IMAGING**, naming **DAVID BRADY, TOM DRISCOLL, JOHN HUNT, DANIEL MARKS, ALEXANDER MROZACK, MATTHEW REYNOLDS, DAVID R. SMITH** as inventors, filed **OCTOBER 11, 2013**, which was filed within the twelve months preceding the filing date of the present application, and the entire content of which is hereby incorporated by reference in its entirety.

[0004] All subject matter of the above applications is incorporated herein by reference to the extent such subject matter is not inconsistent herewith.

BRIEF DESCRIPTION OF THE FIGURES

[0005] **FIG. 1** depicts imaging with a multi-sensor compressive imaging system.

[0006] **FIG. 2A** depicts a Shottky junction-tuned metamaterial element.

[0007] **FIG. 2B** depicts a tunable frequency response of a Shottky junction-tuned metamaterial element.

[0008] **FIG. 3A** depicts a MOSFET-tuned metamaterial element.

[0009] **FIG. 3B** depicts a tunable frequency response of a MOSFET-tuned metamaterial element.

[0010] **FIG. 4** depicts a three-dimensional image combining visual and RF data.

[0011] **FIG. 5** depicts a system block diagram.

DETAILED DESCRIPTION

[0012] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here.

[0013] Compressive imaging systems, such as those described in PCT Application No. PCT/US13/40444, provide an imaging tool suitable for applications including holography, microwave imaging, microwave/mmW imaging, human tracking, security imaging, and threat detection. Embodiments may utilize metamaterial aperture antennas for illuminating a scene and/or measuring a scene, with various examples of metamaterial aperture antennas described in: the above-mentioned PCT application (published as PCT Publication No. WO/2014/025425); A. Bily et al, “Surface Scattering Antennas,” U.S. Patent Publication No. 2012/0194399; and A. Bily et al, “Surface Scattering Antenna Improvements,” U.S. Patent Publication No. 2014/0266946; and P.-Y. Chen et al, “Surface Scattering Antennas with Lumped Elements,” U.S. Application No. 14/506,432; each herein incorporated by reference.

[0014] In some embodiments a compressive imaging system includes both an RF imaging component (such an a metamaterial surface antenna) and an auxiliary sensing component such (as an EO/IR sensor) to provide a multi-sensor integrated imaging system. An illustrative approach is depicted in **FIG. 1**. The figure shows an illumination antenna **100** and a measurement antenna **110** addressing a field of view **120**. This configuration is not intended to be limiting: in other approaches, the same antenna is utilized both for illumination and measurement; in yet other approaches, multiple antennas are utilized for illumination and/or multiple antennas are utilized for measurement.

[0015] In the figure, the field of view is also addressed by an auxiliary sensor unit **150** that is operable to identify a region of interest within the field of view. For example, the sensor unit may include a structured light sensor unit. A structured light sensor, such as a PRIMESENSE sensor or a MICROSOFT KINECT unit (which embeds a PRIMESENSE sensor), can obtain depth information about a scene by projecting a pattern of light (such as infrared light) on the scene and then observing how the pattern falls on the elements of the scene. See, for example, Z. Zalevsky et al., “Method and system for object reconstruction,” U.S. Patent Publication No. 2013/0155195, herein incorporated by reference. The depth information can be used for object recognition, especially to identify the location and/or posture of a human target within the field of view of the sensor unit. See, for example, J. Shotton et al, “Real-time human pose recognition in parts from single depth images,” *Communications of the ACM*, Vol. 56, No. 1, Jan. 2013, pp. 116-124, herein incorporated by reference. In other approaches, the sensor unit may include: other

EO/IR sensors such as a LIDAR unit, an optical camera, a video camera, or a stereo camera; acoustic sensors such as an ultrasonic sonar unit; tactile sensors such as touch-sensitive floor coverings; other RF sensors; or combinations thereof. While the figure depicts a single sensor unit **150**, other embodiments may deploy a plurality of sensor units, e.g. to cover the field of view from multiple vantages (such as front, back, side, top, and/or bottom) or to provide an extended field of view (such as along a corridor).

[0016] The sensor unit **150** may identify a region of interest by determining spatial information about a subject within the field of view **120**. The spatial information can include the position, orientation, or posture of a human subject, and the region of interest may be defined as a volume that encloses or partially encloses the human subject. In the illustrative depiction of **FIG. 1**, this volume is depicted as a box **160** that encloses a subject **161** within the field of view. In other approaches, the volume is a human-shaped volume enclosing and matching the posture of the human subject. In yet other approaches, the volume is determined using a depth map characterizing a surface region of the subject, e.g. as provided by a structured light sensor unit. For example, the volume may be defined as a curved slab-like volume that hugs the contours of the human subject; in other words, for a depth map that defines a two-dimensional manifold corresponding to the surface region, the region of interest is a curved slab corresponding to a three-dimensional neighborhood of the two-dimensional manifold. The thickness of this curved slab may be selected as appropriate for the imaging application, ranging, for example, from about 1 centimeter to about 10 centimeters.

[0017] In the figure, the illumination antenna **100** is depicted as a metamaterial aperture antenna. Various examples of metamaterial aperture antennas are described in the references cited above. In this particular example, the metamaterial aperture antenna is a reconfigurable antenna that includes a two-dimensional waveguide **101** with a plurality of waveguide feeds **102** spatially distributed across the extent of the waveguide. An RF switch **103** is configured to direct RF energy from a radio unit **130** to any of the various feed locations. In the example, the waveguide is coupled to an array of complementary metamaterial elements (not shown) having a diversity of resonance frequencies, e.g. as described in PCT Publication No. WO/2014/025425. In one contemplated mode of operation of this illumination antenna, the RF switch is sequentially adjusted to direct RF energy to each of the various feed locations, and for each position of the RF switch, the radio unit **130** sweeps through a range or set of operating frequencies to utilize the frequency dispersion of the array of complementary metamaterial elements (again as described in PCT Publication No. WO/2014/025425).

[0018] In the figure, the measurement antenna **110** is a horn antenna (or similar medium gain antenna addressing the field of view). In other embodiments, the configuration is swapped: the illumination antenna is a horn antenna (or similar medium gain antenna addressing the field of view) and the measurement antenna is a metamaterial aperture antenna. In yet other embodiments, both the illumination antenna and the measurement antenna are metamaterial aperture antennas. In yet other embodiments, a single metamaterial aperture antenna provides both illumination and measurement. Throughout this disclosure, where details of the illumination antenna and its operation are described, similar details are contemplated for various embodiments of the measurement antenna and its operation, and similar details are contemplated for an antenna that functions both as illumination antenna and measurement antenna.

[0019] In some approaches, the illumination and/or measurement of the scene are performed in the same way regardless of the actual region of interest: the entire field of view is illuminated, and the entire field of view is measured. In other approaches, such as that depicted in **FIG. 1,** the illumination and/or measurement of the scene are tailored in accordance with the identifying of a region of interest by the auxiliary sensor unit. Thus, in the example of **FIG. 1**, when the sensor unit **150** identifies a first region of interest **160** enclosing the position of a subject **161**, the first region of interest **160** is illuminated with a first set of illumination field patterns **171**; when the sensor unit **150** identifies a second region of interest **162** enclosing the position of a subject **163**, the second region of interest **162** is illuminated with a second set of illumination field patterns **172**. The subject **163** may be a second subject within the field of view **120**, or the same subject **161** at a later time (e.g. if the subject is moving through the field of view).

[0020] In various approaches, the illumination antenna is frequency dispersive, reconfigurable, or both. An example of a frequency-dispersive antenna is a metamaterial aperture antenna having a plurality of metamaterial elements arranged on a surface and having a diversity of resonance frequencies, e.g. as described in PCT Publication No. WO/2014/025425. A frequency-dispersive antenna may be operated by sweeping through a set of operating frequencies to illuminate the field of view with a corresponding set of radiation patterns. Alternatively, if it is desirable to concentrate the illumination on a smaller region of interest within the field of view, in some approaches a subset of the operating frequencies may be selected, corresponding to a subset of radiation patterns that are concentrated in the region of interest.

[0021] An example of a reconfigurable antenna is a metamaterial aperture antenna having a plurality of radiation patterns corresponding to a set of antenna configurations that are functions of one or more control inputs. Examples of such antennas are described in PCT Publication No. WO/2014/025425, U.S. Patent Publication No. 2012/0194399, U.S. Patent Publication No. 2014/0266946, and U.S. Application No. 14/506,432, each herein incorporated by reference. In some approaches, the reconfigurable metamaterial aperture antenna has a plurality of adjustable metamaterial elements with respective adjustable physical parameters (such as resonance frequencies and/or Q-factors) that are functions of one or more control inputs. The control inputs may be control voltages for the plurality of scattering elements. A first example of an adjustable metamaterial element is depicted in **FIG. 2A**, which depicts a complementary metamaterial element having an inner conducting region that is electrically isolated from an enclosing conducting region. As depicted in the figure, a pair of Schottky diodes span the gap between the inner conducting region and the enclosing conducting region; a voltage difference applied between the two conductors changes the depletion depths of the diodes, adjusting the resonance frequency and Q-factor of the resonator as shown in **FIG. 2B**. A second example of an adjustable metamaterial element is depicted in **FIG. 3A**, which again depicts a complementary metamaterial element having an inner conducting region that is electrically isolated from an enclosing conducting region, this time with a pair of MOSFETs spanning the gap between the inner conducting region and the enclosing conducting region. As shown in **FIG. 3B**, a voltage applied to the gates of the MOSFETs adjusts the Q-factor of the resonator by altering the conductivity of each MOSFET (the figure depicts full-wave simulation results for the signal transmitted through a microstrip patterned with a single MOSFET-tuned CELC – each curve corresponds to a different source-drain resistance, corresponding to gate voltage). In other approaches described in U.S. Application No. 14/506,432, the metamaterial elements are adjustable by the inclusion of tunable lumped elements such as packaged varactor diodes or HEMT transistors.

[0022] In some approaches the illumination antenna is both frequency-dispersive and reconfigurable. One example is the illumination antenna of **FIG. 1**, which is operable over a set of frequencies and also reconfigurable by adjusting the RF switch. Another example is a frequency-dispersive antenna that is mechanically steered (e.g. by mounting the antenna on a pivot or gimbal, or by directing the antenna energy towards a secondary reflector or refractor that is mechanically steered) or electronically steered (e.g. by directly the antenna energy towards a secondary reflector or refractor that is electronically steered). The reconfigurable antennas of the preceding paragraph are also frequency-dispersive, and may be operated in a set of antenna modes that include both a plurality of frequencies and a plurality of configurations.

[0023] In some approaches a set of illumination antennas is deployed, and one or more of the illumination antennas is selected for the illumination depending on the region of interest. For example, a set of illumination antennas may be deployed along a corridor, and an illumination antenna is selected adjacent to the position of a subject in the corridor.

[0024] After illumination and measurement of the scene, a reconstructed image is obtained using a compressive imaging algorithm, e.g. as described in PCT Publication No. WO/2014/025425. In some approaches, the reconstruction is performed in the same way regardless of the actual region of interest: the minimization problem

$\arg\min_f \|g - Hf\|_2^2 + \lambda R(f)$ for is solved for a reconstructed image f and measurement matrix H defined over the entire field of view. In other approaches, the reconstruction is informed and/or optimized by information received from the auxiliary sensor unit. For example, the measurement matrix H may be truncated to exclude points outside of the region of interest (equivalently, the reconstructed image f is stipulated as zero outside of the region of interest). In some approaches this truncation involves a dimensional reduction of the minimization problem; for example, if the auxiliary sensor unit provides a depth map characterizing a surface region of the subject (e.g. as provided by a structured light sensor unit), the measurement matrix H and reconstructed image f may be defined not in a three-dimensional volume but on a two-dimensional manifold (embedded in three-dimensional space) corresponding to the depth map. Alternatively or additionally, the auxiliary sensor unit can inform the reconstruction by providing boundary conditions for Green's functions of the measurement matrix H; in other words, the Green's functions are recalculated using, for example, the two-dimensional manifold discussed above as a boundary on the space in which the Green's functions are defined.

[0025] In some approaches, particularly in security imaging and threat detection scenarios, the reconstructed image f may be combined with a visual image of the region of interest to provide a multi-spectral representation of the region of interest. For example, the auxiliary sensor unit may provide both a depth map (e.g. as provided by a structure light sensor unit) and an optical image (e.g. as provided by an optical camera), as with the MICROSOFT KINECT sensor unit. Using a graphics processing unit (GPU), the depth map and optical image can be combined with a false-color representation of the reconstructed image f to create a three-dimensional image data object. This three-dimensional object can then be displayed to the user on a monitor. An example is presented in **FIG. 4**, which shows three perspectives of a subject imaged with both a MICROSOFT KINECT and an RF compressive imaging system, In these perspectives, a false-color representation of the RF imaging data is overlaid on a three-dimensional visual image object, showing metallic objects (in this case, keys **401** and a belt buckle **402**) that appear in the RF image.

[0026] In some approaches an interactive user interface, such as a touch screen, allows the user to interact with the three-dimensional image data object and/or select further regions of interest for additional imaging. For example, the user can operate the touch screen interface (or other user interface) to zoom or rotate the three-dimensional image. Alternatively or additionally, the user can operate the touch screen interface (or other user interface) to identify another region of interest (for example, a smaller region of interest addressing a particular feature or portion of the larger region of interest) for subsequent RF imaging. For example, if the initial image data object reveals an area of concern or ambiguity, the user can identify this area of concern or ambiguity (e.g. by drawing a loop on the touch screen) and prompt the imaging system to re-image with a new region of interest corresponding to the identified area.

[0027] With reference now to **FIG. 5**, an illustrative embodiment is depicted as a system block diagram for a multi-sensor compressive imaging system. The system includes an illumination antenna **100** coupled to a transmitter **101** and a measurement antenna **110** coupled to a receiver **111**. The system further includes an auxiliary sensor unit **150**, which may include a EO/IR sensor (such as a MICROSOFT KINECT sensor), an acoustic sensor (such as an ultrasonic sonar unit), a tactile sensor (such as a touch-sensitive floor covering), or combination thereof. The transmitter **101**, receiver **111**, and sensor unit **150** are coupled to processing circuitry **500** configured to reconstruct an image of the region of interest using a compressive imaging algorithm. For embodiments where the illumination antenna is a reconfigurable antenna, the processing circuitry **500** includes control circuitry providing one or more control inputs **102** to the illumination antenna. Similarly, for embodiments where the measurement antenna is a reconfigurable antenna, the processing circuitry **500** includes control circuitry providing one or more control inputs **112** to the measurement antenna. The system optionally includes a monitor **510** coupled to the processing circuitry **500** for display of reconstructed images (optionally combined with a depth map and visual image to provide a projection of a hybrid, false color three dimensional image as discussed above). Finally, the system optionally includes a user interface **520** (schematically depicted as a keyboard, but this schematic representation is not intended to be limiting) coupled to the processing circuitry to allow a user to manipulate displayed images and/or select new regions of interest, as discussed above. In some approaches, the monitor **510** and user interface **520** are combined in the form of a touch-screen monitor.

[0028] The content of the article “Metamaterial Microwave Holographic Imaging System” by Hunt et al., published by the Optical Society of America on October 2014 (J. Opt. Soc. Am. Vol. 31, No. 10), is hereby incorporated by reference in its entirety.

[0029] While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed is:

CLAIMS

1. A method, comprising:
identifying a region of interest within a field of view;
illuminating the region of interest with one or more illumination field patterns;
observing the illuminated region of interest with one or more measurement field patterns; and
reconstructing an image of the region of interest using a compressive imaging algorithm.

2. The method of claim 1, wherein the identifying of the region of interest includes determining spatial information about a subject.

3. The method of claim 2, wherein the determining includes determining by optical or infrared sensing.

4. The method of claim 3, wherein the optical or infrared sensing includes structured light sensing.

5. The method of claim 3, wherein the optical or infrared sensing includes LIDAR sensing.

6. The method of claim 3, wherein the optical or infrared sensing includes photographic or videographic sensing.

7. The method of claim 6, wherein the photographic or videographic sensing includes stereo photographic or videographic sensing.

8. The method of claim 3, wherein the determining including determining by acoustic sensing.

9. The method of claim 3, wherein the determining includes determining by tactile sensing.

10. The method of claim 9, wherein the tactile sensing is subject footstep sensing with a touch-sensitive floor covering.

11. The method of claim 2, wherein the determined spatial information includes subject location information.

12. The method of claim 2, wherein the determined spatial information includes subject orientation information.

13. The method of claim 2, wherein the determined spatial information includes subject posture information.

14. The method of claim 2, wherein the identified region of interest is a volume at least partially enclosing the subject.

15. The method of claim 14, wherein the volume encloses a selected anatomical region of the subject.

16. The method of claim 14, wherein the volume entirely encloses the subject.

17. The method of claim 14, wherein the volume entirely encloses any extent of the subject within the field of view.

18. The method of claim 14, wherein the volume is a polyhedral volume.

19. The method of claim 18, wherein the polyhedral volume is a hexahedral volume.

20. The method of claim 19, wherein the hexahedral volume is a parallelepiped, cuboid, or quadrilateral frustum.

21. The method of claim 2, wherein the determined spatial information includes a depth map characterizing a surface region of the subject.

22. The method of claim 21, wherein the identified region of interest is a volume bounded by the depth map and at least partially enclosing the subject.

23. The method of claim 21, wherein the depth map defines a two-dimensional manifold corresponding to the surface region, and the identified region of interest is a curved slab corresponding to a three-dimensional neighborhood of the two-dimensional manifold.

24. The method of claim 23, wherein the curved slab has a thickness of 15 centimeters or less.

25. The method of claim 23, wherein the curved slab has a thickness of 10 centimeters or less.

26. The method of claim 23, wherein the curved slab has a thickness of 5 centimeters or less.

27. The method of claim 23, wherein the curved slab has a thickness of 1 centimeter or less.

28. The method of claim 1, wherein:

the illuminating of the region of interest includes illuminating the region of interest with the one or more illumination field patterns at one or more RF frequencies; and

the observing of the illuminated region of interest includes observing the region of interest with a one or more measurement field patterns at the one or more RF frequencies.

29. The method of claim 28, w herein the one or more RF frequencies are one or more microwave frequencies.

30. The method of claim 28, wherein the one or more RF frequencies are one or more mmW frequencies.

31. The method of claim 1, wherein the one or more illumination field patterns are radiation patterns of a frequency-dispersive antenna, and the illuminating includes:

illuminating the field of view by operating the frequency-dispersive antenna at each frequency in a set of frequencies.

32. The method of claim 1, wherein the one or more illumination field patterns are radiation patterns of a frequency-dispersive antenna, and the illuminating includes:
selecting a set of frequencies corresponding to a set of illumination patterns that concentrate illumination energy on the region of interest; and
illuminating the region of interest by operating the frequency-dispersive antenna at each frequency in the selected set of frequencies.

33. The method of claim 1, wherein the one or more illumination field patterns are radiation patterns of a reconfigurable antenna, and the illuminating includes:
illuminating the field of view by operating the reconfigurable antenna in each configuration in a set of antenna configurations.

34. The method of claim 1, wherein the one or more illumination field patterns are radiation patterns of a reconfigurable antenna, and the illuminating includes:
selecting a set of antenna configurations corresponding to a set of illumination patterns that concentrate illumination energy on the region of interest;
illuminating the region of interest by operating the reconfigurable antenna in each configuration in the selected set of antenna configurations.

35. The method of claim 1, wherein the one or more illumination field patterns are radiation patterns of a frequency-dispersive, reconfigurable antenna, and the illuminating includes:
illuminating the field of view by operating the frequency-dispersive, reconfigurable antenna in each antenna mode in a set of antenna modes, each mode having a frequency and a configuration.

36. The method of claim 35, wherein the selecting of the set of antenna modes includes selecting a set of frequencies and selecting a set of antenna

configurations, and the selected set of antenna modes is a direct product of the selected set of frequencies and the selected set of antenna configurations.

37. The method of claim 1, wherein the one or more illumination field patterns are radiation patterns of a frequency-dispersive, reconfigurable antenna, and the illuminating includes:

selecting a set of antenna modes, each mode having a frequency and a configuration, the selected set of antenna modes corresponding to a set of illumination patterns that concentrate illumination energy on the region of interest;

illuminating the region of interest by operating the frequency-dispersive, reconfigurable antenna in each antenna mode in the selected set of antenna modes.

38. The method of claim 37, wherein the selecting of the set of antenna modes includes selecting a set of frequencies and selecting a set of antenna configurations, and the selected set of antenna modes is a direct product of the selected set of frequencies and the selected set of antenna configurations.

39. The method of claim 1, wherein the one or more illumination field patterns are radiation patterns of a steerable antenna, and the illuminating includes:

steering the antenna to concentrate illumination energy on the region of interest.

40. The method of claim 39, wherein the steering is a mechanical steering of the antenna.

41. The method of claim 39, wherein the steerable antenna includes a mechanically adjustable reflecting or refracting element, and the steering is a mechanical adjusting of the reflecting or refracting element.

42. The method of claim 39, wherein the steerable antenna includes an electronically adjustable reflecting or refracting element, and the steering is an electronic adjusting of the reflecting or refracting element.

43. The method of claim 1, wherein the illuminating includes:
selecting, from a plurality of illumination antennas, one or more illumination antennas having radiation patterns that concentrate illumination energy on the region of interest; and
illuminating the region of interest by operating the one or more selected illumination antennas.

44. The method of any of claims 31 to 43, wherein the observing is a flood observing with a flood measurement field pattern that fills the field of view.

45. The method of claim 1, wherein the one or more measurement field patterns are radiation patterns of a frequency-dispersive antenna, and the observing includes:
observing the field of view by operating the frequency-dispersive antenna at each frequency in a set of frequencies.

46. The method of claim 1, wherein the one or more measurement field patterns are radiation patterns of a frequency-dispersive antenna, and the observing includes:
selecting a set of frequencies corresponding to a set of measurement field patterns that concentrate measurement sensitivity on the region of interest; and
observing the region of interest by operating the frequency-dispersive antenna at each frequency in the selected set of frequencies.

47. The method of claim 1, wherein the one or more measurement field patterns are radiation patterns of a reconfigurable antenna, and the observing includes:
observing the field of view by operating the reconfigurable antenna in each configuration in a set of antenna configurations.

48. The method of claim 1, wherein the one or more measurement field patterns are radiation patterns of a reconfigurable antenna, and the observing includes:
selecting a set of antenna configurations corresponding to a set of measurement field patterns that concentrate measurement sensitivity on the region of interest; and

observing the region of interest by operating the reconfigurable antenna in each configuration in the selected set of antenna configurations.

49. The method of claim 1, wherein the one or more measurement field patterns are radiation patterns of a frequency-dispersive, reconfigurable antenna, and the observing includes:

observing the field of view by operating the frequency-dispersive, reconfigurable antenna in each antenna mode in a set of antenna modes, each mode having a frequency and a configuration.

50. The method of claim 49, wherein the selecting of the set of antenna modes includes selecting a set of frequencies and selecting a set of antenna configurations, and the selected set of antenna modes is a direct product of the selected set of frequencies and the selected set of antenna configurations.

51. The method of claim 1, wherein the one or more measurement field patterns are radiation patterns of a frequency-dispersive, reconfigurable antenna, and the observing includes:

selecting a set of antenna modes, each mode having a frequency and a configuration, the selected set of antenna modes corresponding to a set of measurement field patterns that concentrate measurement sensitivity on the region of interest; and

observing the region of interest by operating the frequency-dispersive, reconfigurable antenna in each antenna mode in the selected set of antenna modes.

52. The method of claim 51, wherein the selecting of the set of antenna modes includes selecting a set of frequencies and selecting a set of antenna configurations, and the selected set of antenna modes is a direct product of the selected set of frequencies and the selected set of antenna configurations.

53. The method of claim 1, wherein the one or more measurement field patterns are radiation patterns of a steerable antenna, and the observing includes:

steering the antenna to concentrate measurement sensitivity on the region of interest.

54. The method of claim 53, wherein the steering is a mechanical steering of the antenna.

55. The method of claim 53, wherein the steerable antenna includes a mechanically adjustable reflecting or refracting element, and the steering is a mechanical adjusting of the reflecting or refracting element.

56. The method of claim 53, wherein the steerable antenna includes an electronically adjustable reflecting or refracting element, and the steering is an electronic adjusting of the reflecting or refracting element.

57. The method of claim 1, wherein the observing includes:
selecting, from a plurality of measurement antennas, one or more measurement antennas having radiation patterns that concentrate measurement sensitivity on the region of interest; and
observing the region of interest by operating the one or more selected measurement antennas.

58. The method of any of claims 45 to 57, wherein the observing is a flood observing with a flood measurement field pattern that fills the field of view.

59. The method of claim 1, where the illumination field patterns and the measurement field patterns define a measurement matrix H, the observing defines a collection of measurements g, and the compressive imaging algorithm solves the minimization problem $\arg\min_f \|g - Hf\|_2^2 + \lambda R(f)$ for a reconstructed image f, where λ is a regularization parameter and $R(f)$ is a prior knowledge function.

60. The method of claim 59, where the compressive imaging algorithm is a Two-step Iterated Soft Thresholding (TwIST) algorithm.

61. The method of claim 59, where $R(f) = \|f\|_1$.

62. The method of claim 59, wherein the measurement matrix H is defined only within the region of interest and the reconstructed image f is zero outside the region of interest.

63. The method of claim 59, wherein:
the identifying of the region of interest includes determining a depth map characterizing a surface region of a subject;
the depth map defines a two-dimensional manifold corresponding to the surface region; and
the two-dimensional manifold provides a boundary condition for Green's functions of the measurement matrix H.

64. The method of claim 59, wherein:
the identifying of the region of interest includes determining a depth map characterizing a surface region of a subject;
the depth map defines a two-dimensional manifold corresponding to the surface region;
the measurement matrix H is defined only on the two-dimensional manifold; and
the reconstructed image f is a two-dimensional reconstructed image defined on the two-dimensional manifold.

65. The method of claim 21, further comprising:
capturing an optical image of the subject;
combining the depth map, the optical image, and a false-color representation of the reconstructed image to create a three-dimensional image data object.

66. The method of claim 65, further comprising:
displaying the three-dimensional image data object on a monitor.

67. The method of claim 66, further comprising:
zooming or rotating the displayed three-dimensional image data object responsive to a user prompt.

68. The method of claim 67, wherein the monitor is a touch-screen monitor, and the user prompt is a touch-screen gesture.

69. The method of claim 66, further comprising:
identifying a new region of interest responsive to a user prompt.

70. The method of claim 69, further comprising:
illuminating the new region of interest with one or more new illumination field patterns;
observing the illuminated new region of interest with one or more measurement field patterns; and
reconstructing an image of the new region of interest using the compressive imaging algorithm.

71. The method of claim 69, wherein the monitor is a touch-screen monitor, and the user prompt is a touch-screen gesture.

72. A system, comprising:
an illumination antenna having one or more illumination field patterns within a field of view;
a measurement antenna having one or more measurement field patterns within the field of view;
a sensor unit operable to identify a region of interest within the field of view;
a transmitter coupled to an input port of the illumination antenna;
a receiver coupled to an output port of the measurement antenna; and
processing circuitry coupled to the transmitter, the receiver, and the sensor unit and configured to reconstruct an image of the region of interest using a compressive imaging algorithm.

73. The system of claim 72, wherein the sensor unit includes an optical or infrared sensor unit.

74. The system of claim 73, wherein the optical or infrared sensor unit includes a structured light sensor unit.

75. The method of claim 73, wherein the optical or infrared sensor unit includes a LIDAR sensor unit.

76. The system of claim 73, wherein the optical or infrared sensor unit includes an optical or infrared camera.

77. The system of claim 76, wherein the optical or infrared camera is a video camera.

78. The system of claim 73, wherein the optical or infrared camera is a stereo camera.

79. The system of claim 72, wherein the sensor unit includes an acoustic sensor unit.

80. The system of claim 79, wherein the acoustic sensor unit includes an ultrasonic sonar unit.

81. The system of claim 72, wherein the sensor unit includes a tactile sensor unit configured to receive footstep detection signals from a touch-sensitive floor covering.

82. The system of claim 81, further comprising: the touch-sensitive floor covering coupled to the tactile sensor unit and positioned at least partially on a floor under the field of view.

83. The system of claim 72, wherein the illumination antenna is a frequency-dispersive antenna having a set of illumination field patterns corresponding to a set of frequencies.

84. The system of claim 83, wherein the set of frequencies is a set of RF frequencies.

85. The system of claim 84, wherein the set of RF frequencies is a set of microwave frequencies.

86. The system of claim 84, wherein the set of RF frequencies is a set of mmW frequencies.

87. The system of claim 83, wherein the frequency-dispersive antenna is a metamaterial surface antenna having a plurality of metamaterial elements with a diverse plurality of resonance frequencies.

88. The system of claim 87, wherein the metamaterial elements are CELC resonators.

89. The system of claim 72, wherein
the illumination antenna is a reconfigurable antenna having a set of illumination field patterns corresponding to a set of antenna configurations that are functions of one or more control inputs,
and the system further comprises:
illumination control circuitry configured to provide the one or more control inputs.

90. The system of claim 89, wherein the reconfigurable antenna is a metamaterial surface antenna having a plurality of adjustable metamaterial elements with respective adjustable physical parameters that are functions of the one or more control inputs.

91. The system of claim 90, wherein the adjustable metamaterial elements are adjustable complementary metamaterial elements.

92. The system of claim 90, wherein the adjustable metamaterial elements are adjustable subwavelength patch elements.

93. The system of claim 90, wherein the adjustable physical parameters include respective resonance frequencies and/or Q-factors.

94. The system of claim 90, wherein the one or more control inputs include respective control voltages for the plurality of adjustable metamaterial elements.

95. The system of claim 94, wherein the adjustable material elements include lumped elements, and the control voltages are bias voltages for the lumped elements.

96. The system of claim 94, wherein the adjustable metamaterial elements have inner conducting regions that are electrically isolated from enclosing conducting regions, and the respective control voltages are voltage differences between the inner conducting regions and the enclosing conducting regions.

97. The system of claim 96, wherein the adjustable metamaterial elements include electrically adjustable material disposed in neighborhoods of gaps between the inner conducting regions and the enclosing regions.

98. The system of claim 97, wherein the electrically adjustable material includes a liquid crystal material or a ferroelectric material.

99. The system of claim 96, wherein the adjustable metamaterial elements include diodes between the inner conducting regions and the enclosing regions.

100. The system of claim 99, wherein the diodes are Schottky diodes, p-n diodes, or varactor diodes.

101. The system of claim 94, wherein:
the adjustable metamaterial elements have inner conducting regions that are electrically isolated from enclosing conducting regions;
the adjustable metamaterial elements include transistors with sources connected to the inner conducting regions and drains connected to the enclosing conducting regions;
and the respective control voltages are gate voltages for the transistors.

102. The system of claim 101, wherein the transistors are MOSFET or HEMT transistors.

103. The system of claim 72 wherein:
the illumination antenna is a frequency-dispersive, reconfigurable antenna having a set of illumination field patterns corresponding to a set of antenna modes, each antenna mode defined by a frequency and an antenna

configuration, the antenna configurations being functions of one or more control inputs,

and the system further comprises:

illumination control circuitry configured to provide the one or more control inputs.

104. The system of claim 103, wherein the frequency-dispersive, reconfigurable antenna is a metamaterial surface antenna having a plurality of metamaterial elements with a diverse plurality of resonance frequencies, the metamaterial surface antenna including:

a waveguide coupled to the metamaterial elements;

an RF switch having an input port and a set of output ports, and

a respective set of transmission lines connected between the set of output ports and a set of waveguide feeds distributed along the waveguide;

where the RF switch is switchable by the one or more control inputs.

105. The system of claim 72, wherein the illumination antenna is a steerable antenna, and the system further comprises:

steering control circuitry coupled to the steerable antenna and the sensor unit and configured to steer the antenna towards the region of interest.

106. The system of claim 105, wherein the steerable antenna is a mechanically steerable antenna.

107. The system of claim 106, wherein the mechanically steerable antenna is a metamaterial surface antenna attached to a mechanical steering assembly

108. The system of claim 105, wherein the steerable antenna includes a reflecting or refracting structure that is mechanically adjustable to concentrate illumination energy on the region of interest.

109. The system of claim 105, wherein the steerable antenna includes a reflecting or refracting structure that is electronically adjustable to concentrate illumination energy on the region of interest.

110. The system of claim 72, further comprising:

one or more additional illumination antennas, the illumination antenna and the one or more additional illumination antennas constituting a plurality of illumination antennas; and

an RF switch coupling the transmitter to input ports of the plurality of illumination antennas.

111. The system of claim 110, wherein the system further comprises:

illumination control circuitry coupled to the RF switch and the sensor unit and configured to operate the RF switch to select, from the plurality of illumination antennas, an illumination antenna that targets the region of interest.

112. The system of claim 72, wherein the measurement antenna is a frequency-dispersive antenna having a set of measurement field patterns corresponding to a set of frequencies.

113. The system of claim 112, wherein the set of frequencies is a set of RF frequencies.

114. The system of claim 113, wherein the set of RF frequencies is a set of microwave frequencies.

115. The system of claim 113, wherein the set of RF frequencies is a set of mmW frequencies.

116. The system of claim 112, wherein the frequency-dispersive antenna is a metamaterial surface antenna having a plurality of metamaterial elements with a diverse plurality of resonance frequencies.

117. The system of claim 116, wherein the metamaterial elements are CELC resonators.

118. The system of claim 72, wherein
the measurement antenna is a reconfigurable antenna having a set of measurement field patterns corresponding to a set of antenna configurations that are functions of one or more control inputs,
and the system further comprises:
measurement control circuitry configured to provide the one or more control inputs.

119. The system of claim 118, wherein the reconfigurable antenna is a metamaterial surface antenna having a plurality of adjustable metamaterial elements with respective adjustable physical parameters that are functions of the one or more control inputs.

120. The system of claim 119, wherein the adjustable metamaterial elements are adjustable complementary metamaterial elements.

121. The system of claim 119, wherein the adjustable metamaterial elements are adjustable subwavelength patch elements.

122. The system of claim 119, wherein the adjustable physical parameters include respective resonance frequencies and/or Q-factors.

123. The system of claim 119, wherein the one or more control inputs include respective control voltages for the plurality of adjustable metamaterial elements.

124. The system of claim 123, wherein the adjustable material elements include lumped elements, and the control voltages are bias voltages for the lumped elements.

125. The system of claim 123, wherein the adjustable metamaterial elements have inner conducting regions that are electrically isolated from enclosing conducting

regions, and the respective control voltages are voltage differences between the inner conducting regions and the enclosing conducting regions.

126. The system of claim 125, wherein the adjustable metamaterial elements include electrically adjustable material disposed in neighborhoods of gaps between the inner conducting regions and the enclosing regions.

127. The system of claim 126, wherein the electrically adjustable material includes a liquid crystal material or a ferroelectric material.

128. The system of claim 125, wherein the adjustable metamaterial elements include diodes between the inner conducting regions and the enclosing regions.

129. The system of claim 128, wherein the diodes are Schottky diodes, p-n diodes, or varactor diodes.

130. The system of claim 123, wherein:
the adjustable metamaterial elements have inner conducting regions that are electrically isolated from enclosing conducting regions;
the adjustable metamaterial elements include transistors with sources connected to the inner conducting regions and drains connected to the enclosing conducting regions;
and the respective control voltages are gate voltages for the transistors.

131. The system of claim 130, wherein the transistors are MOSFET or HEMT transistors.

132. The system of claim 72 wherein:
the measurement antenna is a frequency-dispersive, reconfigurable antenna having a set of measurement field patterns corresponding to a set of antenna modes, each antenna mode defined by a frequency and an antenna configuration, the antenna configurations being functions of one or more control inputs,
and the system further comprises:

measurement control circuitry configured to provide the one or more control inputs.

133. The system of claim 132, wherein the frequency-dispersive, reconfigurable antenna is a metamaterial surface antenna having a plurality of metamaterial elements with a diverse plurality of resonance frequencies, the metamaterial surface antenna including:

a waveguide coupled to the metamaterial elements;

an RF switch having an input port and a set of output ports, and

a respective set of transmission lines connected between the set of output ports and a set of waveguide feeds distributed along the waveguide;

where the RF switch is switchable by the one or more control inputs.

134. The system of claim 72, wherein the measurement antenna is a steerable antenna, and the system further comprises:

steering control circuitry coupled to the steerable antenna and the sensor unit and configured to steer the antenna towards the region of interest.

135. The system of claim 134, wherein the steerable antenna is a mechanically steerable antenna.

136. The system of claim 135, wherein the mechanically steerable antenna is a metamaterial surface antenna attached to a mechanical steering assembly

137. The system of claim 134, wherein the steerable antenna includes a reflecting or refracting structure that is mechanically adjustable to concentrate measurement sensitivity on the region of interest.

138. The system of claim 134, wherein the steerable antenna includes a reflecting or refracting structure that is electronically adjustable to concentrate measurement sensitivity on the region of interest.

139. The system of claim 72, further comprising:

one or more additional measurement antennas, the measurement antenna and the one or more additional measurement antennas constituting a plurality of measurement antennas; and

an RF switch coupling the receiver to output ports of the plurality of measurement antennas.

140. The system of claim 139, wherein the system further comprises:

measurement control circuitry coupled to the RF switch and the sensor unit and configured to operate the RF switch to select, from the plurality of measurement antennas, a measurement antenna that targets the region of interest.

141. The system of claim 72, wherein:

the sensor unit is configured to provide a depth map and an optical image of a subject in the field of view; and

the processing circuitry includes a graphics processing unit configured to combine the depth map, the optical image, and a false color representation of the reconstructed image as a three-dimensional graphics image object.

142. The system of claim 141, further comprising:

a monitor coupled to the processing circuitry,

wherein the graphics processing unit is configured to display the three-dimensional graphics image object on the monitor.

143. The system of claim 142, wherein the monitor is a touch-screen monitor.

144. The system of claim 143, wherein the graphics processing unit is configured to zoom or rotate the three-dimensional graphics image object responsive to a gesture on the touch-screen monitor.

145. The system of claim 141, further comprising: a user interface coupled to the processing circuitry.

146. The system of claim 145, wherein the graphics processing unit is configured to zoom or rotate the three-dimensional graphics image object responsive to an input from the user interface.

147. A system, comprising:
an antenna having a set of radiation patterns within a field of view;
a sensor unit operable to identify a region of interest within the field of view;
a transceiver coupled to the antenna; and
processing circuitry coupled to the transceiver and the sensor unit and configured to reconstruct an image of the region of interest using a compressive imaging algorithm.

148. The system of claim 147, wherein the sensor unit includes an optical or infrared sensor unit.

149. The system of claim 148, wherein the optical or infrared sensor unit includes a structured light sensor unit.

150. The method of claim 148, wherein the optical or infrared sensor unit includes a LIDAR sensor unit.

151. The system of claim 148, wherein the optical or infrared sensor unit includes an optical or infrared camera.

152. The system of claim 151, wherein the optical or infrared camera is a video camera.

153. The system of claim 151, wherein the optical or infrared camera is a stereo camera.

154. The system of claim 147, wherein the sensor unit includes an acoustic sensor unit.

155. The system of claim 154, wherein the acoustic sensor unit includes an ultrasonic sonar unit.

156. The system of claim 147, wherein the sensor unit includes a tactile sensor unit configured to receive footstep detection signals from a touch-sensitive floor covering.

157. The system of claim 156, further comprising: the touch-sensitive floor covering coupled to the tactile sensor unit and positioned at least partially on a floor under the field of view.

158. The system of claim 147, wherein the antenna is a frequency-dispersive antenna having a set of radiation patterns corresponding to a set of frequencies.

159. The system of claim 158, wherein the set of frequencies is a set of RF frequencies.

160. The system of claim 159, wherein the set of RF frequencies is a set of microwave frequencies.

161. The system of claim 159, wherein the set of RF frequencies is a set of mmW frequencies.

162. The system of claim 158, wherein the frequency-dispersive antenna is a metamaterial surface antenna having a plurality of metamaterial elements with a diverse plurality of resonance frequencies.

163. The system of claim 162, wherein the metamaterial elements are CELC resonators.

164. The system of claim 147, wherein
the antenna is a reconfigurable antenna having a set of radiation patterns
corresponding to a set of antenna configurations that are functions of one or more control inputs,
and the system further comprises:
control circuitry configured to provide the one or more control inputs.

165. The system of claim 164, wherein the reconfigurable antenna is a metamaterial surface antenna having a plurality of adjustable metamaterial elements with respective adjustable physical parameters that are functions of the one or more control inputs.

166. The system of claim 165, wherein the adjustable metamaterial elements are adjustable complementary metamaterial elements.

167. The system of claim 165, wherein the adjustable metamaterial elements are adjustable subwavelength patch elements.

168. The system of claim 165, wherein the adjustable physical parameters include respective resonance frequencies and/or Q-factors.

169. The system of claim 165, wherein the one or more control inputs include respective control voltages for the plurality of adjustable metamaterial elements.

170. The system of claim 169, wherein the adjustable material elements include lumped elements, and the control voltages are bias voltages for the lumped elements.

171. The system of claim 169, wherein the adjustable metamaterial elements have inner conducting regions that are electrically isolated from enclosing conducting regions, and the respective control voltages are voltage differences between the inner conducting regions and the enclosing conducting regions.

172. The system of claim 170, wherein the adjustable metamaterial elements include electrically adjustable material disposed in neighborhoods of gaps between the inner conducting regions and the enclosing regions.

173. The system of claim 171, wherein the electrically adjustable material includes a liquid crystal material or a ferroelectric material.

174. The system of claim 170, wherein the adjustable metamaterial elements include diodes between the inner conducting regions and the enclosing regions.

175. The system of claim 173, wherein the diodes are Schottky diodes, p-n diodes, or varactor diodes.

176. The system of claim 169, wherein:
the adjustable metamaterial elements have inner conducting regions that are electrically isolated from enclosing conducting regions;
the adjustable metamaterial elements include transistors with sources connected to the inner conducting regions and drains connected to the enclosing conducting regions;
and the respective control voltages are gate voltages for the transistors.

177. The system of claim 175, wherein the transistors are MOSFET or HEMT transistors.

178. The system of claim 147, wherein:
the antenna is a frequency-dispersive, reconfigurable antenna having a set of radiation patterns corresponding to a set of antenna modes, each antenna mode defined by a frequency and an antenna configuration, the antenna configurations being functions of one or more control inputs,
and the system further comprises:
control circuitry configured to provide the one or more control inputs.

179. The system of claim 177, wherein the frequency-dispersive, reconfigurable antenna is a metamaterial surface antenna having a plurality of metamaterial elements with a diverse plurality of resonance frequencies, the metamaterial surface antenna including:
a waveguide coupled to the metamaterial elements;
an RF switch having an input port and a set of output ports, and
a respective set of transmission lines connected between the set of output ports and a set of waveguide feeds distributed along the waveguide;
where the RF switch is switchable by the one or more control inputs.

180. The system of claim 147, wherein the antenna is a steerable antenna, and the system further comprises:
steering control circuitry coupled to the steerable antenna and the sensor unit and configured to steer the antenna towards the region of interest.

181. The system of claim 179, wherein the steerable antenna is a mechanically steerable antenna.

182. The system of claim 180, wherein the mechanically steerable antenna is a metamaterial surface antenna attached to a mechanical steering assembly

183. The system of claim 179, wherein the steerable antenna includes a reflecting or refracting structure that is mechanically adjustable to target the region of interest.

184. The system of claim 179, wherein the steerable antenna includes a reflecting or refracting structure that is electronically adjustable to target the region of interest.

185. The system of claim 147, further comprising:
one or more additional antennas, the antenna and the one or more additional antennas constituting a plurality of antennas; and
an RF switch coupling the transceiver to the plurality of antennas.

186. The system of claim 184, wherein the system further comprises:
control circuitry coupled to the RF switch and the sensor unit and configured to operate the RF switch to select, from the plurality of antennas, an antenna that targets the region of interest.

187. The system of claim 147, wherein:
the sensor unit is configured to provide a depth map and an optical image of a subject in the field of view; and
the processing circuitry includes a graphics processing unit configured to combine the depth map, the optical image, and a false color representation of the reconstructed image as a three-dimensional graphics image object.

188. The system of claim 186, further comprising:

a monitor coupled to the processing circuitry,

wherein the graphics processing unit is configured to display the three-dimensional graphics image object on the monitor.

189. The system of claim 187, wherein the monitor is a touch-screen monitor.

190. The system of claim 188, wherein the graphics processing unit is configured to zoom or rotate the three-dimensional graphics image object responsive to a gesture on the touch-screen monitor.

191. The system of claim 187, further comprising: a user interface coupled to the processing circuitry.

192. The system of claim 190, wherein the graphics processing unit is configured to zoom or rotate the three-dimensional graphics image object responsive to an input from the user interface.

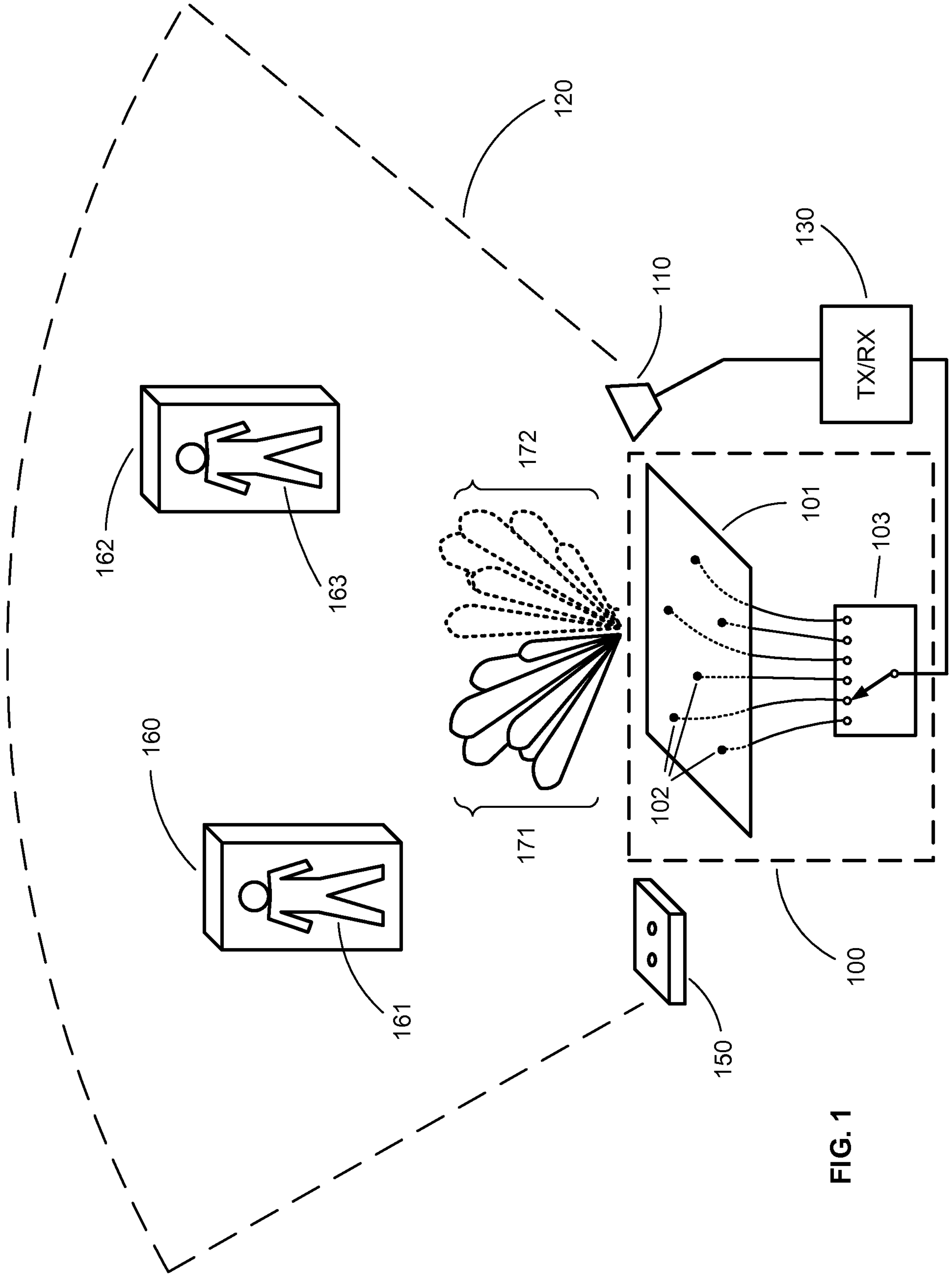


FIG. 1

FIG. 2A

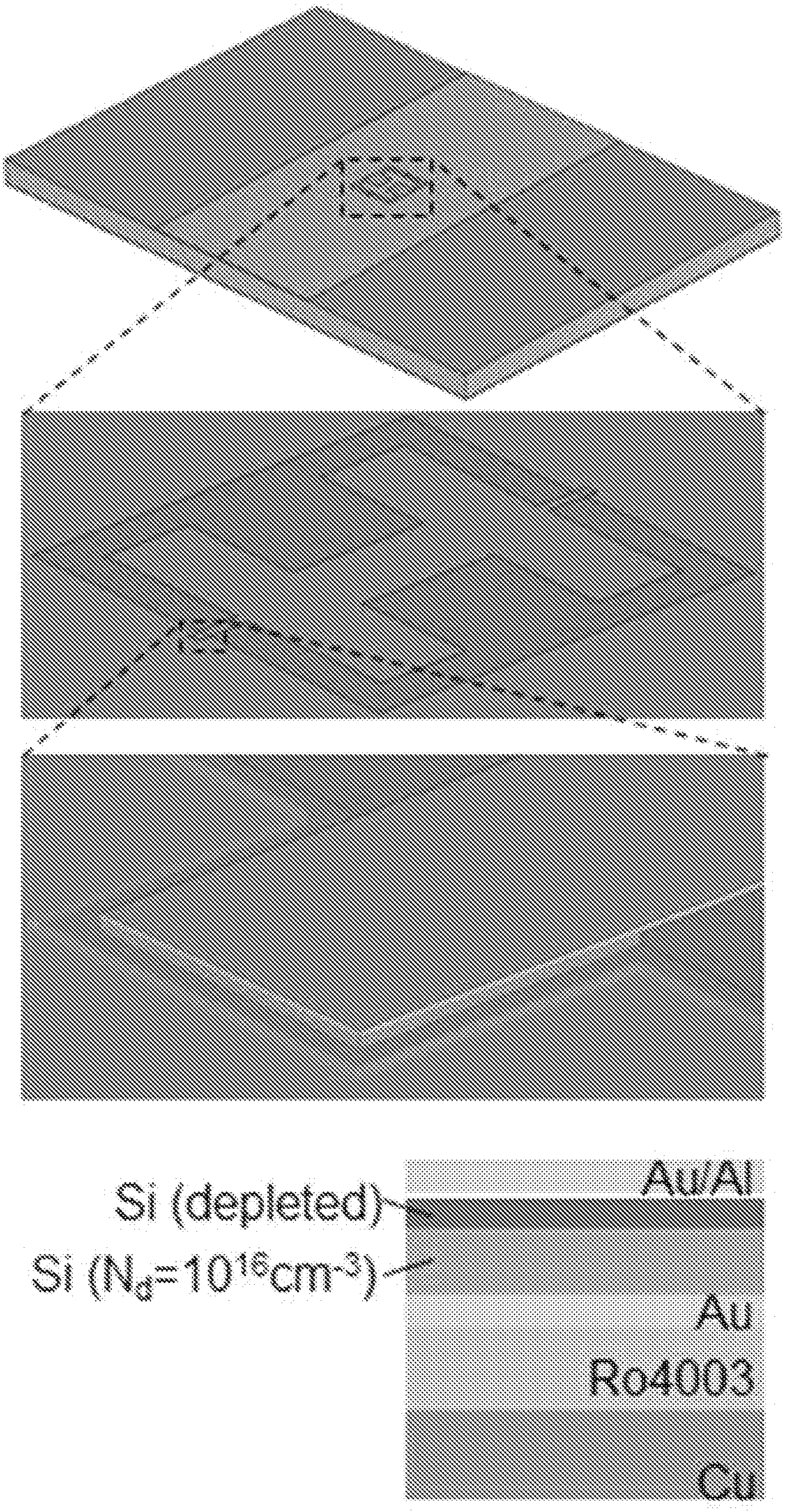


FIG. 2B

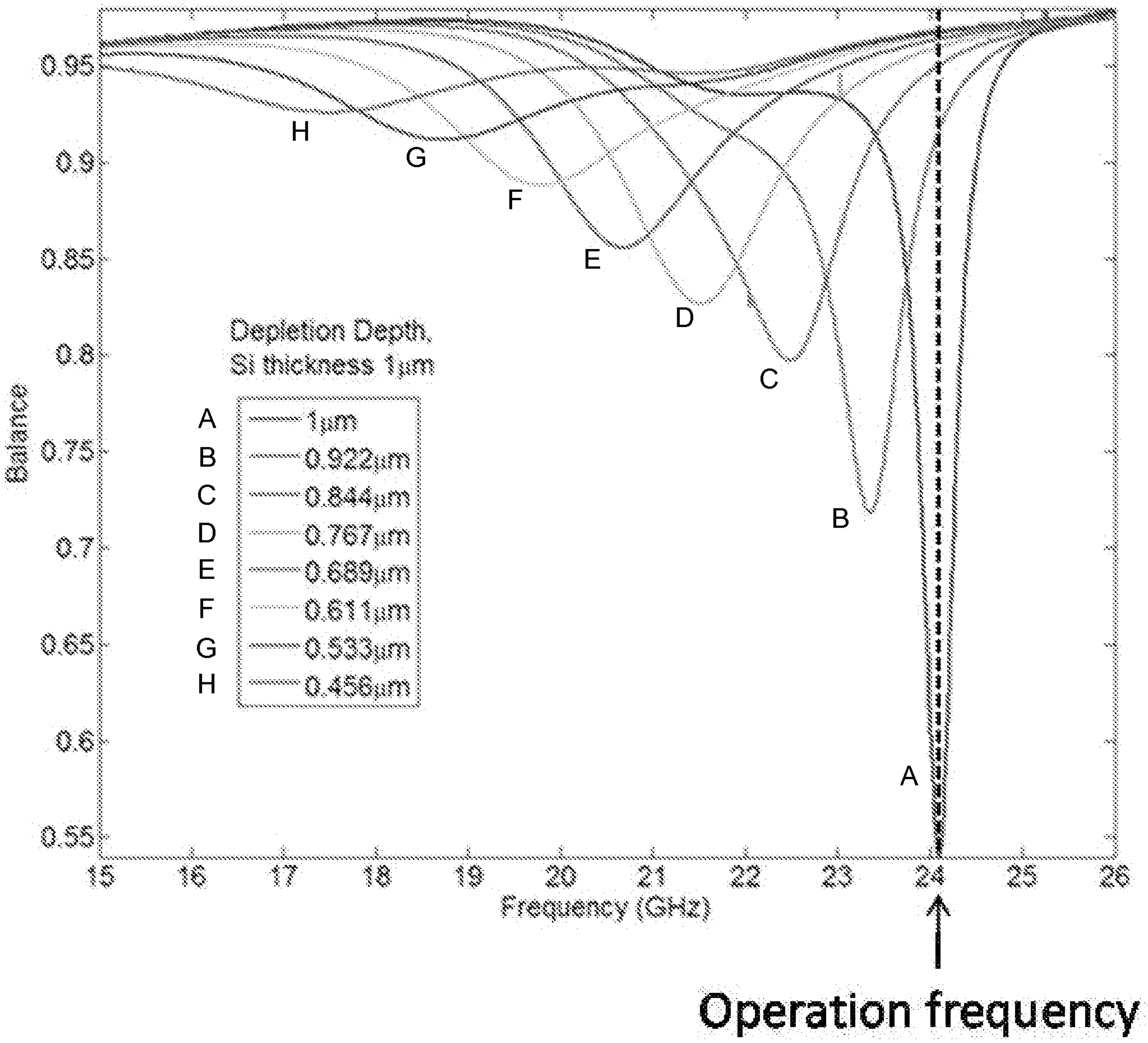
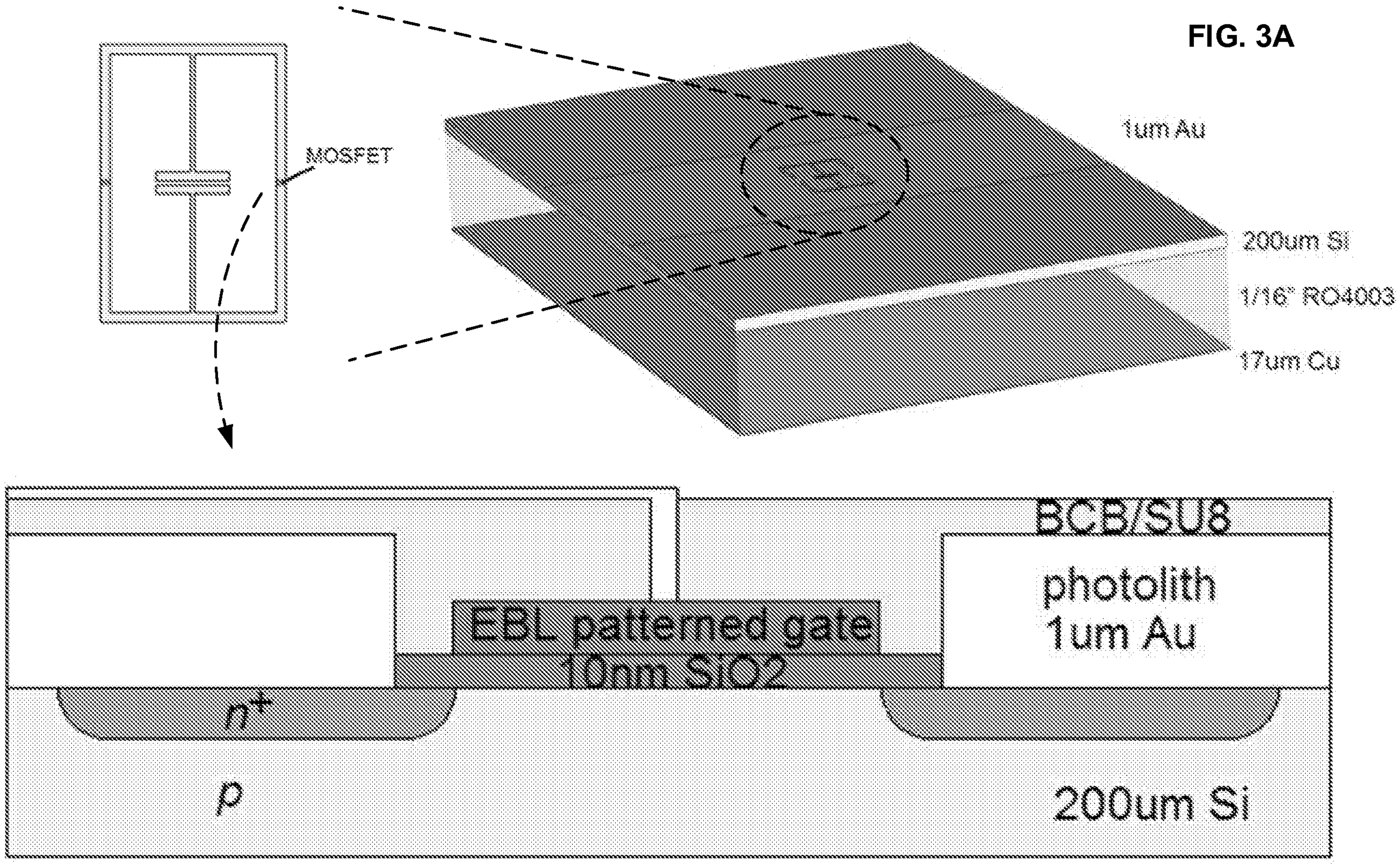
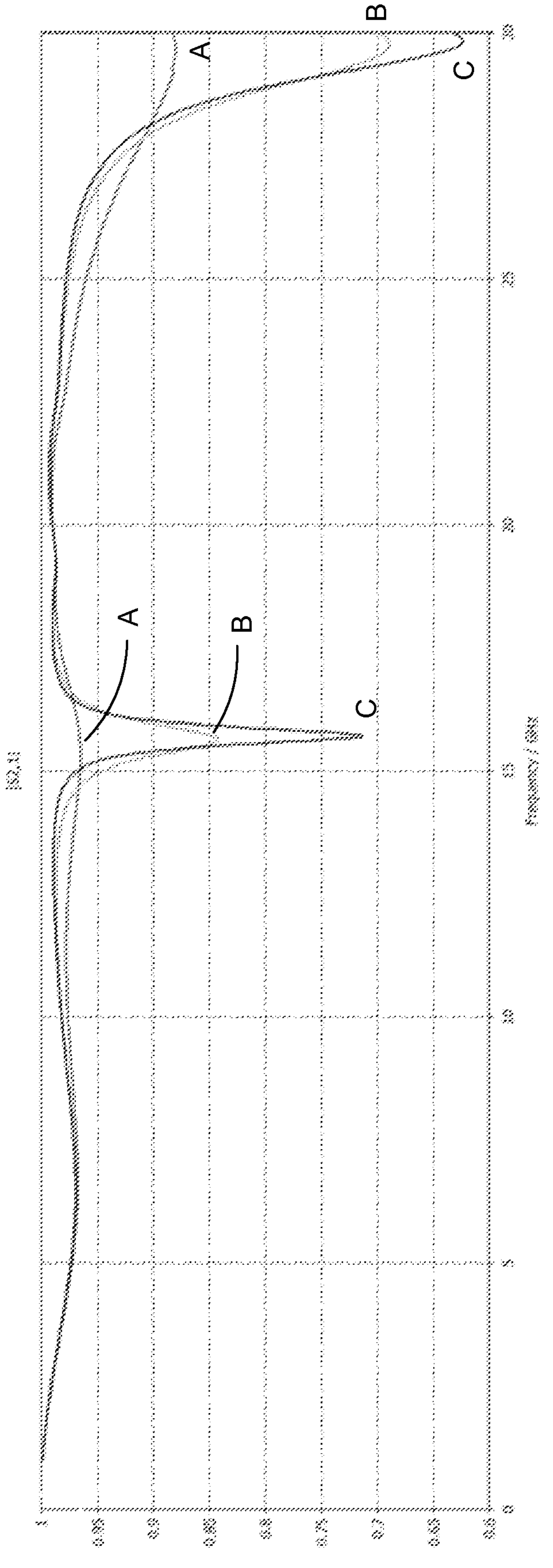

Depletion Depth,
Si thickness 1µm
A 1µm
B 0.922µm
C 0.844µm
D 0.767µm
E 0.689µm
F 0.611µm
G 0.533µm
H 0.456µm
Balance
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
15
16
17
18
19
20
21
22
23
24
25
26
Frequency (GHz)
A
B
C
D
E
F
G
H
Operation frequency

FIG. 3A


1um Au
200um Si
1/16" RO4003
17um Cu
MOSFET
BCB/SU8
photolith
1um Au
EBL patterned gate
10nm SiO2
n^+
p
200um Si



(A = 10^2 ohms, B = 10^3 ohms, C = 10^4 ohms)

FIG. 3B

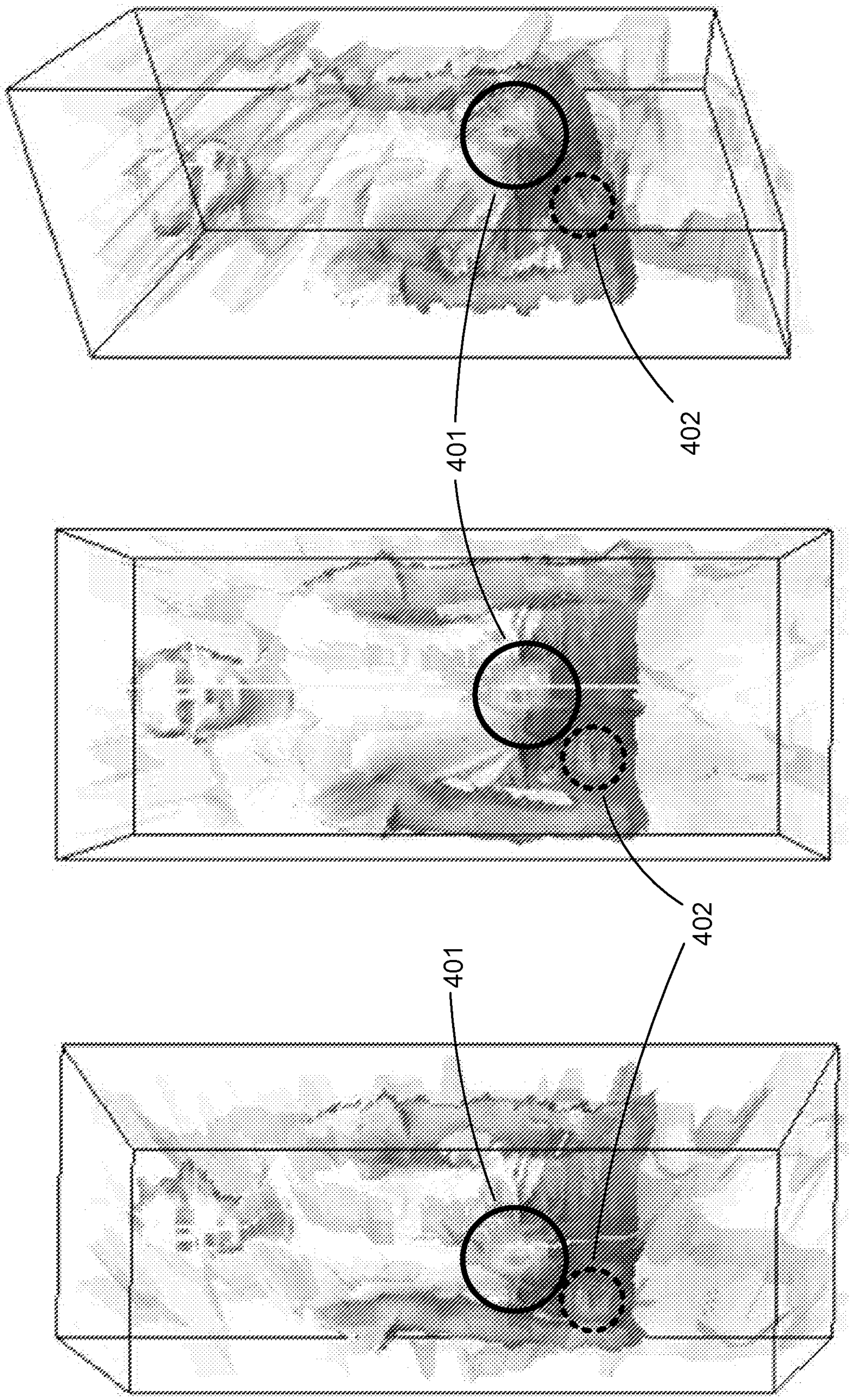


FIG. 4

FIG. 5