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(54) **Title**: COMBINATION OF AN X-RAY TUBE AND A SOURCE GRATING WITH ELECTRON BEAM MANIPULATION

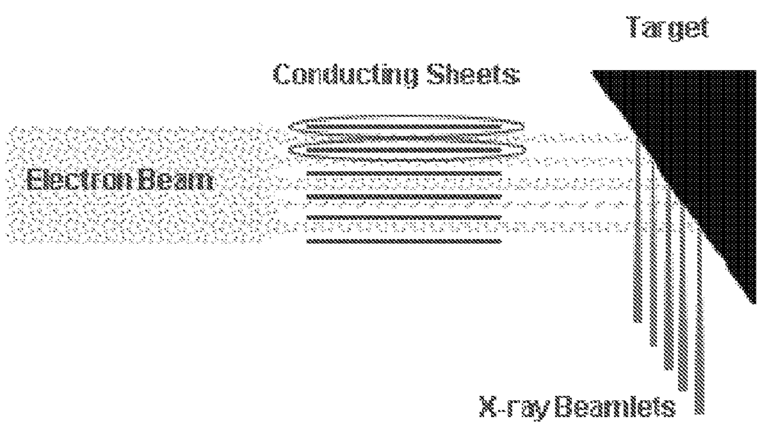

FIG. 5B

(57) **Abstract**: Novel and advantageous systems and methods for performing X-ray imaging by using an X-ray source with source grating functionality incorporated therein are provided. An electron beam can be electromagnetically manipulated such that the X-ray source emits radiation in a pattern that is the same as if the radiation had already passed through a source grating.

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DESCRIPTION

COMBINATION OF AN X-RAY TUBE AND A SOURCE GRATING WITH ELECTRON BEAM MANIPULATION

CROSS-REFERENCE TO A RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application Serial No. 62/197,301, filed July 27, 2015, which is incorporated herein by reference in its entirety.

BACKGROUND

X-ray imaging is a powerful tool in many fundamental and practical applications. As a primary example, X-ray computed tomography (CT) is a cornerstone of modern hospitals and clinics. The dominating theory of X-ray imaging is generally based on the attenuation contrast mechanism.

X-ray gratings have been used for hybrid CT imaging in terms of attenuation, refraction, and small-angle scattering. This grating-based approach represents a paradigm shift in X-ray CT from gray-scale (attenuation) to true-color (attenuation, refraction, and small-angle scattering, which is also referred to as dark-field, and spectral) imaging.

In conventional X-ray imaging, the image contrast arises from varying linear attenuation coefficients. Attenuation-contrast-based imaging exhibits good performance only when strong attenuators are embedded in a weakly absorbing matrix, such as in the cases of bone-tissue and tissue-air interfaces. However, biological soft tissues include mainly light elements (e.g., hydrogen, carbon, nitrogen, and oxygen), and their compositions are quite homogeneous with little density variation. The attenuation-contrast between soft tissue features is often insufficient to reflect pathological changes.

In particular, many healthy tissues display similar characteristics in current X-ray images as those of diseased tissues, such as tumors. For example, fibro-glandular tissue can have a density of 1.035 cm^{-3} and an attenuation coefficient of 0.80 cm^{-1}, and cancerous tissue can have a density of 1.045 cm^{-3} and an attenuation coefficient of 0.85

cm^{-1}. Given inherent measurement noise, it is challenging to discern such cancerous tissue from the healthy tissue, as well as other soft tissue features such as those reflecting musculoskeletal healing. Therefore, attenuation-contrast-based imaging is unable to differentiate early-stage tumors and soft tissues.

Use of X-ray gratings can provide for not only attenuation but also phase-contrast and dark-field information. An X-ray grating-based imaging approach typically includes an ordinary X-ray source, and a source grating (often known as G0), and a phase grating (often known as G1) and an analyzer grating (often known as G2) are also typically used. The main purpose of the source grating is to provide sufficient spatial coherence for differential phase-contrast imaging. The source grating can have a micrometer-range period, such as a period of 50 μm or about 50 μm. It is difficult, however, to make a high-quality and large area source grating.

BRIEF SUMMARY

Embodiments of the subject invention provide novel and advantageous systems and methods for performing X-ray imaging by using an X-ray source with source grating functionality incorporated therein (e.g., via electromagnetic manipulation of the electron beam(s) within the X-ray source). The X-ray source can be, for example, an X-ray tube, though embodiments are not limited thereto. The systems and methods of embodiments of the subject invention present new opportunities in phase-contrast X-ray imaging (or X-ray grating-based imaging), shorten X-ray grating-based imaging time, increase configuration flexibility, increase efficiency of heat management, increase cost-effective ness, and have many applications, including biomedical applications.

In an embodiment, an imaging system can comprise an X-ray radiation source having source grating functionality incorporated therein, such that the X-ray source is configured to emit X-ray radiation in a pattern that is indistinguishable from that of X-ray radiation that would have passed through a source grating whose functionality has been incorporated into the X-ray source. The system can further comprise a detector, a phase grating positioned between the X-ray source and the detector, and an analyzer grating positioned between the phase grating and the detector, and the system can specifically exclude a source grating.

In another embodiment, a system as described herein can be used to perform a method of imaging, the method comprising: providing X-ray radiation to a sample to be imaged using the X-ray radiation source; collecting the X-ray radiation with a detector; and analyzing data from the detector to obtain an image. X-ray diffraction fringes, phase-shift information, and dark-field information can be extracted from the data from the detector.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a grating-based X-ray interferometer that can be used in X-ray grating-based imaging.

Figure 2 shows a cross-sectional view of components of an X-ray imaging system for demonstrating principles of non-absorption grating X-ray phase-contrast imaging.

Figure 3 shows a cross-sectional view of a cathode ray tube.

Figure 4 shows a cutaway view of a portion of a focusing element that can be used in an X-ray source according to an embodiment of the subject invention.

Figure 5A shows a perspective view of a scheme for manipulating an electron beam within an X-ray source according to an embodiment of the subject invention.

Figure 5B shows a top view of the scheme shown in Figure 5A.

Figure 6 shows a view of beam focusing within an X-ray source according to an embodiment of the subject invention.

DETAILED DESCRIPTION

Embodiments of the subject invention provide novel and advantageous systems and methods for performing X-ray imaging by using an X-ray source with source grating functionality incorporated therein (e.g., via electromagnetic manipulation of the electron beam(s) within the X-ray source). The X-ray source can be, for example, an X-ray tube, though embodiments are not limited thereto. The systems and methods of embodiments of the subject invention present new opportunities in phase-contrast X-ray imaging (or X-ray grating-based imaging), shorten X-ray grating-based imaging time, increase configuration flexibility, increase efficiency of heat management, increase cost-effectiveness, and have many applications, including biomedical applications.

Figure 1 shows a grating-based X-ray interferometer that can be used in X-ray grating-based imaging (phase-contrast X-ray imaging). Figure 1 is from Burger et al. (Optics Express 22, 32107-32118 2014; which is hereby incorporated herein by reference in its entirety). Referring to Figure 1, the interferometer can include an X-ray source and a source grating **G0**. The system can also include a phase grating **G1**, an analyzer grating **G2**, and a detector. The sample being imaged can be placed between the source grating **G0** and the phase grating **G1**. Phase-shift and dark-field information can be extracted, for example using phase stepping, where the analyzer grating **G2** or phase grating **G1** is scanned over one **G2** grating period. The subject application shares some concepts with International Patent Application No. PCT/US2016/043154 (Wang et al.), which is hereby incorporated by reference herein in its entirety.

Figure 2 shows a cross-sectional view of components of an X-ray imaging system and demonstrates principles of non-absorption phase-contrast X-ray grating-based imaging. The system can include a source grating **G0** (e.g., a ladder-shaped multi-line source grating), a phase grating **G1**, an analyzer grating **G2**, and a detector, which can be a structured scintillator. Figure 2 is from Du et al. (Optics Express, 22669, November 2011; which is hereby incorporated herein by reference in its entirety).

Referring again to Figure 1, to improve the efficiency of the system, the source grating **G0** can be combined with the X-ray source (e.g., an X-ray tube). An X-ray source typically includes a metallic target (anode or anode target), and the source grating (G0) configuration could be implemented in the metallic target inside the X-ray source. However, embodiments of the subject invention can combine the functionality of the source grating **G0** with the X-ray source by electromagnetically manipulating the electron beam(s) within the X-ray source (e.g., instead of implementing the source grating (G0) configuration in the metallic target). That is, the X-ray source can achieve a G0 grating effect with the normal metallic target within the X-ray source through the use of electron beam manipulation.

A key idea related to embodiments of the subject invention is that an electron beam can be easily controlled, for example with coils. Thus, a controlled electron beam can implement the G0 effect within the X-ray source in a flexible and cost-effective manner that does not require complex components. The electron beam(s) can be controlled based on electromagnetic theory and techniques that are known and understood in a general sense. In addition, micro-fabrication technologies and/or nano-fabrication technologies can be used with embodiments of the subject invention. For example, graphene and/or nanotubes can be used with an X-ray source (e.g., for fine-tuning the electro-magnetic field such that the electron beam(s) are transmitted in a desirable configuration towards the metallic target in the source).

In many embodiments, a scanning mechanism can be implemented in the X-ray source (e.g., an X-ray tube). One or more electron beams can be electromagnetically manipulated or steered within the X-ray source to implement or trace a G0 grating pattern (i.e., to implement the functionality of the source grating within the X-ray source). The X-ray source can be configured such that the electron beam manipulation can occur before the electron beam(s) reach the metallic target within the X-ray source. In this way, the X-rays exiting the X-ray source can in the same state as those that have passed through the source grating in a conventional system that includes an X-ray source and a separate source grating. In an embodiment, an electron beam can be manipulated or steered within the X-ray source to implement or trace a G0 grating pattern such that the beam is split into a plurality of beamlets and nominal beamlets are wider than gaps between the beamlets.

Embodiments of the subject invention include X-ray sources that can emulate many different types of source gratings, including one-dimensional (1D) gratings, two-dimensional (2D) gratings, and three-dimensional (3D) gratings. In addition, X-ray sources of embodiments of the subject invention can the shape of an electron beam within the X-ray source. For example, a circular electron beam (i.e., a cross-section of the beam taken through a plane perpendicular to the direction of propagation of the beam is circular) can be electromagnetically manipulated and converted into a different shape beam, such as a planar beam or a flat beam (i.e., a cross-section of the beam taken through a plane perpendicular to the direction of propagation of the beam has a shape of a line and a cross-section of the beam taken through a plane parallel to the direction of propagation of the beam has a shape of a plane or rectangle).

Figure 4 shows a cutaway view of a portion of a focusing element that can be used in an X-ray source according to an embodiment of the subject invention. Referring to Figure 4, the focusing element **200** can be shaped such that the incoming electron beam **310** (depicted as including a plurality of individual electron orbits) can be focused into a different shape or configuration in the outgoing electron beam **320**. As depicted in Figure 4, the focusing element **200** can be a solenoid having an aperture **210** (e.g., an elliptical aperture) through which the electron beam passes, and the incoming electron beam **310** can be circular and can be transformed into a flat or planar outgoing electron beam **320**. These depictions are for exemplary purposes, and embodiments are not limited thereto. It should also be noted that Figure 4 is a cutaway showing only a portion of a focusing element **200**; in this case the pole-piece of the solenoid is depicted.

According to embodiments of the subject invention, an electron beam can be focused into many different shapes, including but not limited to a focal point or a planar sheet. The electron beam can be electromagnetically steered to the metallic target. For example, the beam can be split into a plurality of beamlets such that beamlets are wider than gaps between the beamlets. As another example, the beam can be split into a plurality of beamlets such that beamlets are narrower than gaps between the beamlets. In either of these examples, the widths of the beamlets and the widths of the gaps between the beamlets can each be uniform, non-uniform, or a mixture thereof.

In the case of implementing the functionality of a 1D source grating into the X-ray source, a scanning electron sheet results in much higher X-ray flux than a scanning electron focal spot. That is, if the beam is focused into a sheet shape, the X-ray flux can be higher than if it is focused into a spot shape. In certain instances, focusing into a sheet shape may be easier to accomplish than focusing into a spot.

In an embodiment, an electron beam can be focused into a set of electron sheets (e.g., a set of parallel electron sheets). The original beam can have a large aperture and can go through an electromagnetic grating within the X-ray source to be split into multiple electron sheets (or tall, very narrow beams).

Because electrons are negatively charged, when manipulating an electron beam in an X-ray source according to embodiments of the subject invention, the original electrons of the beam must be steered through a negatively-charged pattern (e.g., a periodic pattern) to be deflected into the desired configuration. For example, a set of parallel sheets or rods can be negatively charged so that incoming electrons will be repelled from these negatively-charged barriers and pass between them, forming the desired configuration of the electron flow. The structures used to steer the electron beam(s) (e.g., sheets, rods, coils) can be made of any suitable material. In certain embodiments, the structures used to steer the electron beam(s) (e.g., sheets, rods, coils) can be made of graphene or carbon nanotubes. For example, sheets can be made of graphene, and rods can be made of nanotubes, though embodiments are not limited thereto.

Figure 3 shows a cross-sectional view of a cathode ray tube and is from Circuits Today (http://www.circuitstoday.com/crt-cathode-ray-tube; which is hereby incorporated herein by reference in its entirety). The cathode ray tube can include an electron gun for producing a stream of electrons, focusing and accelerating anodes for producing a narrow and sharply focused electron beam, horizontal and vertical deflection plates for controlling the beam path, and an evacuated glass envelope with a phosphorescent screen that produces visible light when struck by a high velocity electron beam.

In an embodiment of the subject invention, the concept of a cathode ray tube can be enhanced and used in an X-ray tube as an X-ray source. The source grating (G0) of an X-ray imaging system can be integrated into the X-ray tube so that the X-ray tube directly emits spatially-coherent X-ray beams as if they are already through the source grating (G0).

In an X-ray source as described herein, the anode target can have any suitable shape. For example, the anode target can be shaped as at least one spot, at least one line, or an extended area. In a particular embodiment, the anode target can have the same area as the source grating (G0) that would otherwise be present in the imaging system (i.e., the source grating whose functionality is being implemented in the X-ray source). As an example, the source grating (G0) in an X-ray imaging system typically has an area of about 50-500 mm^2 (e.g., 15 mm by 15 mm = 225 mm^2), and the period of the source grating (G0) is typically in a range of from 15 μm to 80 μm. An anode target can therefore have an area in a range of from 50 mm^2 to 500 mm^2 (e.g., 15 mm by 15 mm = 225 mm^2), and the X-ray source can be configured to produce X-rays as if they had already gone through a source grating (G0) having a period in a range of from 15 μm to 80 μm.

An electron beam can be focused within the X-ray source to any suitable pattern. For example, an electron beam can be focused into a focal spot with a small radius (e.g., a radius of 5 μm, or less than 6 μm). The accelerated electron beam can hit the anode target in a progressive scan mode that traces the transmission pattern of the source grating (G0) whose functionality is being incorporated into the X-ray source, creating a sufficiently coherent virtual line source. This concept is shown in Figure 6, in which an electron beam **610** can be focused into a focal spot **630** to generate coherent X-rays. The focal spot **630** can be electromagnetically scanned to trace the transmission pattern of the G0 grating whose functionality is being incorporated into the X-ray source. In Figure 6, reference numeral **400** is the cathode, reference numeral **500** is the focusing element (e.g., focusing plate), and reference numeral **700** is the anode target.

The limiting factor for single exposure in a scheme as depicted in Figure 6 can be the heat capacity of the focal spot. In an embodiment of the subject invention, the exposure time can be short at each focal spot. For example, the exposure time at each focal spot can be less than 10 milliseconds (ms), less than 5, ms, less than 2 ms, less than 1 ms, about 1 ms, or 1 ms. If the exposure time at each focal spot is 1 ms, it can take 1 second to scan a grid line of the G0 grating (that would otherwise be present) (e.g., if it takes 1000 focal spots to make up a grid line). At this scanning speed, if there are 10 grid lines, it can take 10 seconds to scan over the entire grating that would otherwise be present. The heat storage capacity of an anode target can be, for example, about 115,000 heat units (HU). For a 100 kVp, 5 mA X-ray tube, the heat generated by the electric beam hitting the anode target can be calculated from HU = 100 kV × 5 mA × 0.001 seconds = 0.5 HU. This is significantly lower than the heat storage capacity of the anode target (115,000 HU), so a static anode can be a valid option, which significantly reduces the design and fabrication cost of the X-ray source.

Embodiments of the subject invention provide systems and methods for performing imaging by using a radiation source with source grating functionality incorporated therein (e.g., via electromagnetic manipulation of the electron beam(s) within the radiation source). The systems and methods of embodiments of the subject invention present new opportunities in phase-contrast X-ray imaging, shorten phase-contrast X-ray imaging time, increase configuration flexibility, increase efficiency of heat management, increase cost-effectiveness, and have many applications, including biomedical applications.

The methods and processes described herein can be embodied as code and/or data. The software code and data described herein can be stored on one or more computer-readable media, which may include any device or medium that can store code and/or data for use by a computer system. When a computer system reads and executes the code and/or data stored on a computer-readable medium, the computer system performs the methods and processes embodied as data structures and code stored within the computer-readable storage medium.

It should be appreciated by those skilled in the art that computer-readable media include removable and non-removable structures/devices that can be used for storage of information, such as computer-readable instructions, data structures, program modules, and other data used by a computing system/environment. A computer-readable medium includes, but is not limited to, volatile memory such as random access memories (RAM, DRAM, SRAM); and non-volatile memory such as flash memory, various read-only-memories (ROM, PROM, EPROM, EEPROM), magnetic and ferromagnetic/ferroelectric memories (MRAM, FeRAM), and magnetic and optical storage devices (hard drives, magnetic tape, CDs, DVDs); network devices; or other media now known or later developed that is capable of storing computer-readable information/data. Computer-readable media should not be construed or interpreted to include any propagating signals. A computer-readable medium of the subject invention can be, for example, a compact disc (CD), digital video disc (DVD), flash memory device, volatile memory, or a hard disk drive (HDD), such as an external HDD or the HDD of a computing device, though embodiments are not limited thereto. A computing device can be, for example, a laptop computer, desktop computer, server, cell phone, or tablet, though embodiments are not limited thereto.

The subject invention includes, but is not limited to, the following exemplified embodiments.

Embodiment 1. An imaging system, comprising:

a radiation source (e.g., an X-ray source) having source grating functionality incorporated therein, such that the radiation source is configured to (electromagnetically manipulate an electron beam therein such that the X-ray source) emit(s) radiation (e.g., spatially-coherent X-ray beams or beamlets) in a pattern that is indistinguishable from that of radiation (e.g., X-ray beams or beamlets) that would have passed through a source grating whose functionality has been incorporated into the radiation source.

Embodiment 2. The system according to embodiment 1, further comprising a detector for detecting radiation (e.g., X-rays) from the radiation source.

Embodiment 3. The system according to embodiment 2, further comprising a phase grating positioned between the radiation source and the detector.

Embodiment 4. The system according to embodiment 3, further comprising an analyzer grating positioned between the phase grating and the detector.

Embodiment 5. The system according to embodiment 2, further comprising an analyzer grating positioned between the radiation source and the detector.

Embodiment 6. The system according to any of embodiments 3-4, configured such that a subject to be imaged is positioned between the radiation source and the phase grating or between the phase grating and the detector.

Embodiment 7. The system according to any of embodiments 1-6, wherein the system excludes a source grating.

Embodiment 8. The system according to any of embodiments 1-7, wherein the radiation source is configured to manipulate an electron beam within the radiation source to trace a pattern of the source grating whose functionality has been incorporated into the radiation source.

Embodiment 9. The system according to embodiment 8, wherein the radiation source is configured to manipulate the electron beam within the radiation source before the electron beam reaches a metallic (anode) target of the radiation source.

Embodiment 10. The system according to any of embodiments 1-7, wherein the radiation source comprises a metallic (anode) target that is in a motion mode (e.g., rotation mode).

Embodiment 11. The system according to any of embodiments 1-10, wherein the radiation source comprises at least one negatively-charged structure configured to steer the electron beam into a desirable (e.g., predetermined) pattern within the radiation source.

Embodiment 12. The system according to embodiment 11, wherein the at least one negatively-charged structure configured to steer the electron beam within the radiation source comprises a plate configured to split an electron beam (e.g., into a one-dimensional (1D) array of beamlets or a two-dimensional (2D) array of beamlets).

Embodiment 13. The system according to any of embodiments 11-12, wherein the at least one negatively-charged structure configured to steer the electron beam within the radiation source comprises a rod.

Embodiment 14. The system according to any of embodiments 11-13, wherein the at least one negatively-charged structure configured to steer the electron beam within the radiation source comprises a coil.

Embodiment 15. The system according to any of embodiments 11-14, wherein the radiation source comprises a plurality of negatively-charged structures configured to steer the electron beam within the radiation source.

Embodiment 16. The system according to embodiment 15, wherein the plurality of negatively-charged structures configured to steer the electron beam within the radiation source comprises a set of parallel plates configured to split an electron beam into a plurality of electron sheets.

Embodiment 17. The system according to any of embodiments 15-16, wherein the plurality of negatively-charged structures configured to steer the electron beam within the radiation source comprises a set of rods (which can be parallel to each other) configured to split an electron beam.

Embodiment 18. The system according to any of embodiments 15-17, wherein the plurality of negatively-charged structures configured to steer the electron beam within the radiation source comprises a set of coils.

Embodiment 19. The system according to any of embodiments 11-18, wherein the at least one negatively-charged structure configured to steer the electron beam within the radiation source comprises a negatively-charged structure comprising graphene.

Embodiment 20. The system according to any of embodiments 11-19, wherein the at least one negatively-charged structure configured to steer the electron beam within the radiation source comprises a negatively-charged structure comprising carbon nanotubes.

Embodiment 21. The system according to any of embodiments 11-20, wherein the at least one negatively-charged structure configured to steer the electron beam within the radiation source comprises a negatively-charged structure comprising a metal material.

Embodiment 22. The system according to any of embodiments 11-18, wherein each negatively-charged structure (configured to steer the electron beam within the radiation source) present comprises graphene.

Embodiment 23. The system according to any of embodiments 11-18, wherein each negatively-charged structure (configured to steer the electron beam within the radiation source) present comprises carbon nanotubes.

Embodiment 24. The system according to any of embodiments 11-18, wherein each negatively-charged structure (configured to steer the electron beam within the radiation source) present comprises a metal material.

Embodiment 25. The system according to any of embodiments 11-21, wherein each plate present in the at least one negatively-charged structure (configured to steer the electron beam within the radiation source) comprises graphene.

Embodiment 26. The system according to any of embodiments 11-21, wherein each rod present in the at least one negatively-charged structure (configured to steer the electron beam within the radiation source) comprises carbon nanotubes.

Embodiment 27. The system according to any of embodiments 11-21, wherein each coil present in the at least one negatively-charged structure (configured to steer the electron beam within the radiation source) comprises a metal material.

Embodiment 28. The system according to any of embodiments 1-27, wherein the radiation source comprises a metallic (anode) target, and wherein the target has a shape of at least one spot, at least one line, or an extended area.

Embodiment 29. The system according to embodiment 28, wherein the target has a shape of at least one spot.

Embodiment 30. The system according to embodiment 28, wherein the target has a shape of at least one line.

Embodiment 31. The system according to embodiment 28, wherein the target has a shape of an extended area.

Embodiment 32. The system according to embodiment 31, wherein the target has an area that is equal to that of the source grating whose functionality has been incorporated into the radiation source.

Embodiment 33. The system according to any of embodiments 31-32, wherein the target has an area in a range of from 50 mm^2 to 500 mm^2.

Embodiment 34. The system according to any of embodiments 31-33, wherein the target has an area of 225 mm^2 (or about 225 mm^2).

Embodiment 35. The system according to any of embodiments 31-34, wherein the target is a 15 mm by 15 mm target.

Embodiment 36. The system according to any of embodiments 1-35, wherein the source grating whose functionality has been incorporated into the radiation source has a period in a range of from 15 μm to 80 μm.

Embodiment 37. The system according to any of embodiments 1-36, wherein the source grating whose functionality has been incorporated into the radiation source has a period of 50 μm (or about 50 μm).

Embodiment 38. The system according to any of embodiments 1-37, wherein the radiation source comprises a focusing element configured to focus an electron beam into a desired shape.

Embodiment 39. The system according to any of embodiments 1-37, wherein the radiation source comprises a focusing element configured to focus an electron beam into a desired shape on a (the) metallic target within the radiation source.

Embodiment 40. The system according to embodiment 39, wherein the desired shape is a focal spot with a radius of less than 20 μm.

Embodiment 41. The system according to embodiment 39, wherein the desired shape is a focal spot with a radius of less than 6 μm.

Embodiment 42. The system according to embodiment 39, wherein the desired shape is a focal spot with a radius of 5 μm (or about 5 μm).

Embodiment 43. The system according to embodiment 39, wherein the desired shape is a line, such that the electron beam is focused into a flat beam.

Embodiment 44. The system according to any of embodiments 38-39, wherein the desired shape is a(t least one) line, such that the electron beam is focused into a flat beam.

Embodiment 45. The system according to any of embodiments 37-44, wherein the focusing element is a focusing plate.

Embodiment 46. The system according to any of embodiments 37-44, wherein the focusing element comprises at least one focusing plate.

Embodiment 47. The system according to any of embodiments 37-44, wherein the focusing element comprises a plurality of focusing plates.

Embodiment 48. The system according to any of embodiments 37-44, wherein the focusing element comprises a solenoid with an aperture therethrough.

Embodiment 49. The system according to embodiment 48, wherein the aperture is elliptical.

Embodiment 50. The system according to any of embodiments 40-42, wherein the radiation source is configured such that an exposure time for each focal spot is less than 10 milliseconds (ms).

Embodiment 51. The system according to any of embodiments 40-42, wherein the radiation source is configured such that an exposure time for each focal spot is less than 5 ms.

Embodiment 52. The system according to any of embodiments 40-42, wherein the radiation source is configured such that an exposure time for each focal spot is less than 2 ms.

Embodiment 53. The system according to any of embodiments 40-42, wherein the radiation source is configured such that an exposure time for each focal spot is less than 1 ms.

Embodiment 54. The system according to any of embodiments 40-42, wherein the radiation source is configured such that an exposure time for each focal spot is 1 ms (or about 1 ms).

Embodiment 55. The system according to any of embodiments 1-54, wherein the radiation source comprises a metallic target that is a static anode or a rotating anode.

Embodiment 56. The system according to any of embodiments 1-55, wherein the radiation source is configured to split an electron beam into a plurality of beamlets such each beamlet is wider than each gap between the beamlets.

Embodiment 57. The system according to any of embodiments 1-55, wherein the radiation source is configured to split an electron beam into a plurality of beamlets such each beamlet is narrower than each gap between the beamlets.

Embodiment 58. The system according to any of embodiments 56-57, wherein the width of each beamlet is the same as that of every other beamlet.

Embodiment 59. The system according to any of embodiments 56-58, wherein a width of each gap between beamlets is the same as that of every other gap between beamlets.

Embodiment 60. The system according to any of embodiments 56-57, wherein the width of at least one beamlet is the same as that of at least one other beamlet.

Embodiment 61. The system according to any of embodiments 56-57 and 60, wherein a width of at least one gap between beamlets is the same as at least one other gap between beamlets.

Embodiment 62. The system according to any of embodiments 56-57, wherein the width of each beamlet is different from that of every other beamlet.

Embodiment 63. The system according to any of embodiments 56-57 and 62, wherein a width of each gap between beamlets is different from that of every other gap between beamlets.

Embodiment 64. The system according to any of embodiments 1-63, wherein the source grating whose functionality has been incorporated into the radiation source is a 1D source grating.

Embodiment 65 The system according to any of embodiments 1-63, wherein the source grating whose functionality has been incorporated into the radiation source is a 2D source grating.

Embodiment 66. A method of imaging using the system according to any of embodiments 1-65, the method comprising:

providing radiation (e.g., X-ray radiation) to a sample to be imaged using the radiation source;

collecting the radiation (e.g., X-ray radiation) with a (the) detector; and

analyzing data from the detector to obtain an image.

Embodiment 67. The method according to embodiment 66, wherein analyzing data from the detector to obtain an image comprises extracting diffraction fringes (e.g., X-ray diffraction fringes), phase-shift information, and dark-field information from the data from the detector.

Embodiment 68. The system according to any of embodiments 1-65, further comprising a (non-transitory) machine readable medium (e.g., computer readable medium) having machine-executable (e.g., computer executable) instructions (stored thereon) for performing the step of analyzing data from the detector according to the method of any of embodiments 66-67, wherein the machine readable medium is in operable communication with the detector.

Embodiment 69. The system according to any of embodiments 1-65 and 68, or the method according to any of embodiments 66-67, wherein a (the) detector of the imaging system is a photon-counting detector, such that spectral information is included in data of the detector.

When the term “about” is used herein, in conjunction with a numerical value, it is understood that the value can be in a range of 95% of the value to 105% of the value, i.e. the value can be +/- 5% of the stated value. For example, “about 1 kg” means from 0.95 kg to 1.05 kg.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

All patents, patent applications, provisional applications, and publications referred to or cited herein (including those in the “References” section) are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

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Wang et al., International Patent Application No. PCT/US2016/043154

CLAIMS

What is claimed is:

1. An imaging system, comprising:

an X-ray source having source grating functionality incorporated therein, such that the X-ray source is configured to electromagnetically manipulate an electron beam therein such that the X-ray source emits X-ray radiation in a pattern that is indistinguishable from that of X-ray radiation that would have passed through a source grating whose functionality has been incorporated into the X-ray source.

2. The system according to claim 1, further comprising a detector for detecting X-rays from the X-ray source.

3. The system according to claim 2, further comprising a phase grating positioned between the X-ray source and the detector.

4. The system according to claim 3, further comprising an analyzer grating positioned between the phase grating and the detector.

5. The system according to claim 2, further comprising an analyzer grating positioned between the X-ray source and the detector.

6. The system according to any of claims 3-4, configured such that a subject to be imaged is positioned between the X-ray source and the phase grating or between the phase grating and the detector.

7. The system according to any of claims 1-6, wherein the system excludes a source grating.

8. The system according to any of claims 1-7, wherein the X-ray source is configured to manipulate an electron beam within the X-ray source to trace a pattern of the source grating whose functionality has been incorporated into the X-ray source.

9. The system according to claim 8, wherein the X-ray source is configured to manipulate the electron beam within the X-ray source before the electron beam reaches a metallic target of the X-ray source.

10. The system according to any of claims 1-7, wherein the X-ray source comprises a metallic target that is in rotation mode or another motion mode.

11. The system according to any of claims 1-10, wherein the X-ray source comprises at least one negatively-charged structure configured to steer the electron beam into a predetermined pattern within the X-ray source.

12. The system according to claim 11, wherein the at least one negatively-charged structure configured to steer the electron beam within the X-ray source comprises a plate configured to split an electron beam into a one-dimensional (1D) array of beamlets or a two-dimensional (2D) array of beamlets.

13. The system according to any of claims 11-12, wherein the at least one negatively-charged structure configured to steer the electron beam within the X-ray source comprises a rod.

14. The system according to any of claims 11-13, wherein the at least one negatively-charged structure configured to steer the electron beam within the X-ray source comprises a coil.

15. The system according to any of claims 11-14, wherein the radiation source comprises a plurality of negatively-charged structures configured to steer the electron beam within the X-ray source.

16. The system according to claim 15, wherein the plurality of negatively-charged structures configured to steer the electron beam within the X-ray source comprises a set of parallel plates configured to split an electron beam into a plurality of electron sheets.

17. The system according to any of claims 15-16, wherein the plurality of negatively-charged structures configured to steer the electron beam within the X-ray source comprises a set of rods configured to split an electron beam.

18. The system according to any of claims 15-17, wherein the plurality of negatively-charged structures configured to steer the electron beam within the X-ray source comprises a set of coils.

19. The system according to any of claims 11-18, wherein the at least one negatively-charged structure configured to steer the electron beam within the X-ray source comprises a negatively-charged structure comprising graphene.

20. The system according to any of claims 11-19, wherein the at least one negatively-charged structure configured to steer the electron beam within the X-ray source comprises a negatively-charged structure comprising carbon nanotubes.

21. The system according to any of claims 11-20, wherein the at least one negatively-charged structure configured to steer the electron beam within the X-ray source comprises a negatively-charged structure comprising a metal material.

22. The system according to any of claims 11-18, wherein each negatively-charged structure configured to steer the electron beam within the X-ray source comprises graphene.

23. The system according to any of claims 11-18, wherein each negatively-charged structure configured to steer the electron beam within the X-ray source comprises carbon nanotubes.

24. The system according to any of claims 11-18, wherein each negatively-charged structure configured to steer the electron beam within the X-ray source comprises a metal material.

25. The system according to any of claims 11-21, wherein each plate present in the at least one negatively-charged structure configured to steer the electron beam within the X-ray source comprises graphene.

26. The system according to any of claims 11-21, wherein each rod present in the at least one negatively-charged structure configured to steer the electron beam within the X-ray source comprises carbon nanotubes.

27. The system according to any of claims 11-21, wherein each coil present in the at least one negatively-charged structure configured to steer the electron beam within the X-ray source comprises a metal material.

28. The system according to any of claims 1-27, wherein the X-ray source comprises a metallic target, and wherein the target has a shape of at least one spot, at least one line, or an extended area.

29. The system according to claim 28, wherein the target has a shape of at least one spot.

30. The system according to claim 28, wherein the target has a shape of at least one line.

31. The system according to claim 28, wherein the target has a shape of an extended area.

32. The system according to claim 31, wherein the target has an area that is equal to that of the source grating whose functionality has been incorporated into the radiation source.

33. The system according to any of claims 31-32, wherein the target has an area in a range of from 50 mm^2 to 500 mm^2.

34. The system according to any of claims 31-33, wherein the target has an area of about 225 mm^2.

35. The system according to any of claims 31-34, wherein the target is a 15 mm by 15 mm target.

36. The system according to any of claims 1-35, wherein the source grating whose functionality has been incorporated into the X-ray source has a period in a range of from 15 μm to 80 μm.

37. The system according to any of claims 1-36, wherein the source grating whose functionality has been incorporated into the X-ray source has a period of about 50 μm.

38. The system according to any of claims 1-37, wherein the X-ray source comprises a focusing element configured to focus an electron beam into a desired shape.

39. The system according to any of claims 1-37, wherein the X-ray source comprises a focusing element configured to focus an electron beam into a desired shape on the metallic target within the X-ray source.

40. The system according to claim 39, wherein the desired shape is a focal spot with a radius of less than 20 μm.

41. The system according to claim 39, wherein the desired shape is a focal spot with a radius of less than 6 μm.

42. The system according to claim 39, wherein the desired shape is a focal spot with a radius of about 5 μm.

43. The system according to claim 39, wherein the desired shape is a line, such that the electron beam is focused into a flat beam.

44. The system according to any of claims 38-39, wherein the desired shape is at least one line, such that the electron beam is focused into a flat beam.

45. The system according to any of claims 37-44, wherein the focusing element is a focusing plate.

46. The system according to any of claims 37-44, wherein the focusing element comprises at least one focusing plate.

47. The system according to any of claims 37-44, wherein the focusing element comprises a plurality of focusing plates.

48. The system according to any of claims 37-44, wherein the focusing element comprises a solenoid with an aperture therethrough.

49. The system according to claim 48, wherein the aperture is elliptical.

50. The system according to any of claims 40-42, wherein the X-ray source is configured such that an exposure time for each focal spot is less than 10 milliseconds (ms).

51. The system according to any of claims 40-42, wherein the X-ray source is configured such that an exposure time for each focal spot is less than 5 ms.

52. The system according to any of claims 40-42, wherein the X-ray source is configured such that an exposure time for each focal spot is less than 2 ms.

53. The system according to any of claims 40-42, wherein the X-ray source is configured such that an exposure time for each focal spot is less than 1 ms.

54. The system according to any of claims 40-42, wherein the X-ray source is configured such that an exposure time for each focal spot is about 1 ms.

55. The system according to any of claims 1-54, wherein the X-ray source comprises a metallic target that is a static anode or a rotating anode.

56. The system according to any of claims 1-55, wherein the X-ray source is configured to split an electron beam into a plurality of beamlets such each beamlet is wider than each gap between the beamlets.

57. The system according to any of claims 1-55, wherein the X-ray source is configured to split an electron beam into a plurality of beamlets such each beamlet is narrower than each gap between the beamlets.

58. The system according to any of claims 56-57, wherein the width of each beamlet is the same as that of every other beamlet.

59. The system according to any of claims 56-58, wherein a width of each gap between beamlets is the same as that of every other gap between beamlets.

60. The system according to any of claims 56-57, wherein the width of at least one beamlet is the same as that of at least one other beamlet.

61. The system according to any of claims 56-57 and 60, wherein a width of at least one gap between beamlets is the same as at least one other gap between beamlets.

62. The system according to any of claims 56-57, wherein the width of each beamlet is different from that of every other beamlet.

63. The system according to any of claims 56-57 and 62, wherein a width of each gap between beamlets is different from that of every other gap between beamlets.

64. The system according to any of claims 1-63, wherein the source grating whose functionality has been incorporated into the radiation source is a 1D source grating.

65 The system according to any of claims 1-63, wherein the source grating whose functionality has been incorporated into the radiation source is a 2D source grating.

66. A method of imaging using the system according to any of claims 1-65, the method comprising:

providing X-ray radiation to a sample to be imaged using the X-ray source;

collecting the X-ray with a detector of the system; and

analyzing data from the detector to obtain an image.

67. The method according to claim 66, wherein analyzing data from the detector to obtain an image comprises extracting X-ray diffraction fringes, phase-shift information, and dark-field information from the data from the detector.

68. The system according to any of claims 1-65, further comprising a machine readable medium having machine-executable instructions stored thereon for performing the step of analyzing data from the detector according to the method of any of claims 66-67, wherein the machine readable medium is in operable communication with the detector.

69. The system according to any of claims 1-65 and 68, or the method according to any of claims 66-67, wherein a detector of the imaging system is a photon-counting detector, such that spectral information is included in data of the detector.

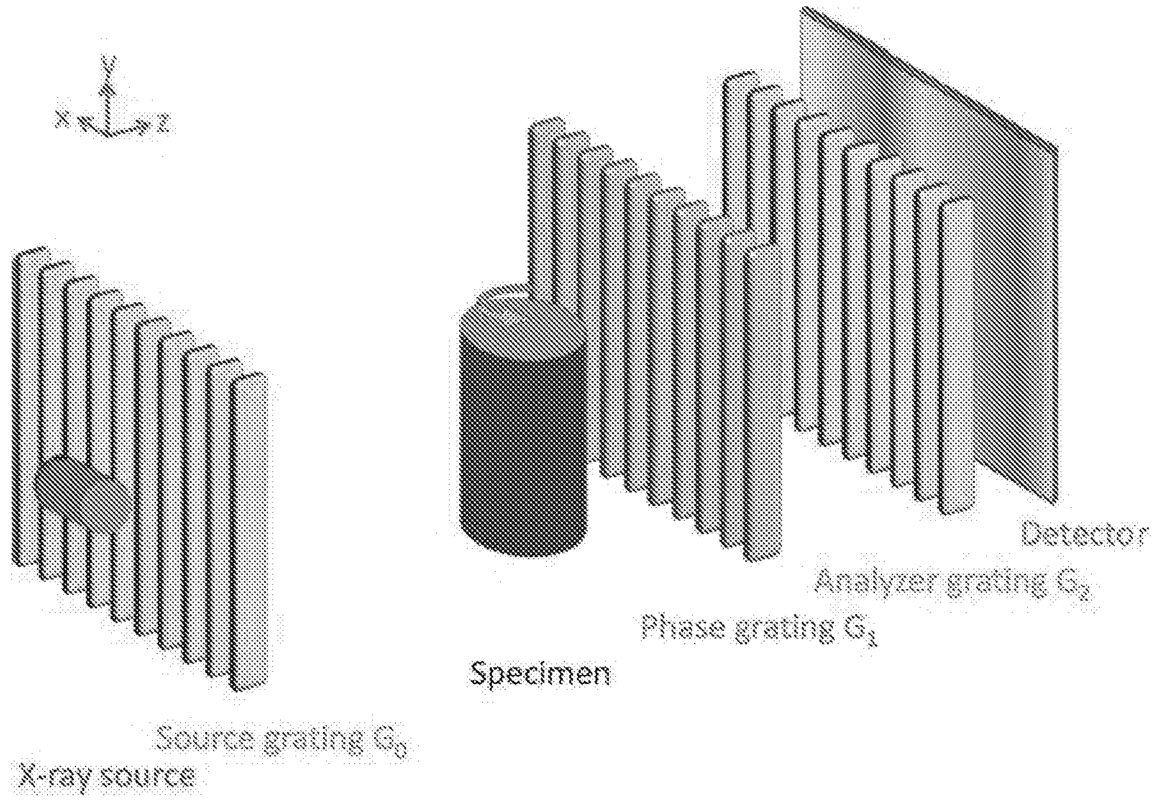
y
x
z
Detector
Analyzer grating G_2
Phase grating G_1
Specimen
Source grating G_0
X-ray source

FIG. 1

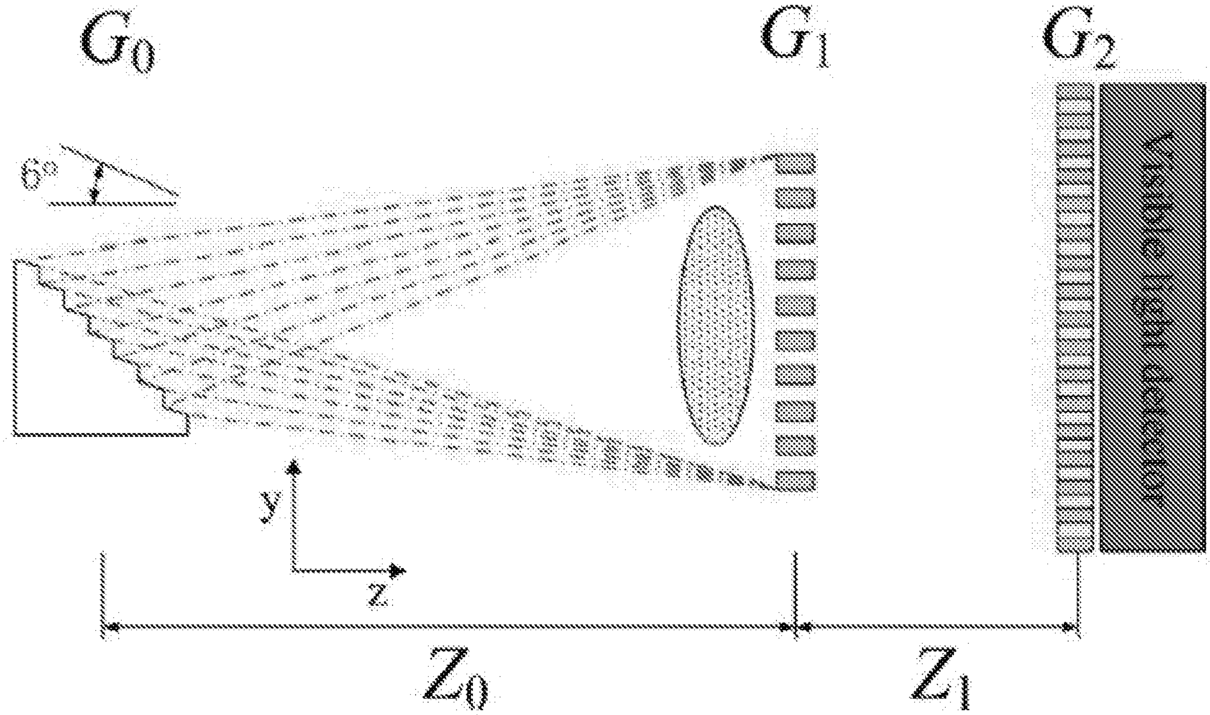
G_0
G_1
G_2
6º
Visible light detector
y
z
Z_0
Z_1

FIG. 2

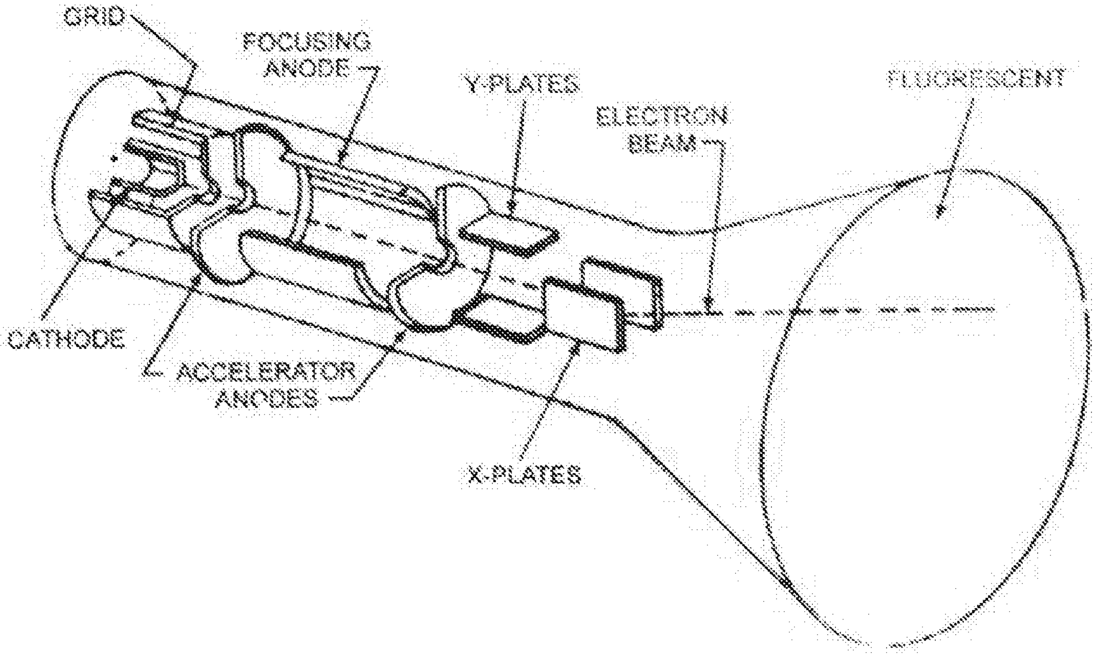
GRID
FOCUSING
ANODE
Y-PLATES
ELECTRON
BEAM
FLUORESCENT
CATHODE
ACCELERATOR
ANODES
X-PLATES

FIG. 3

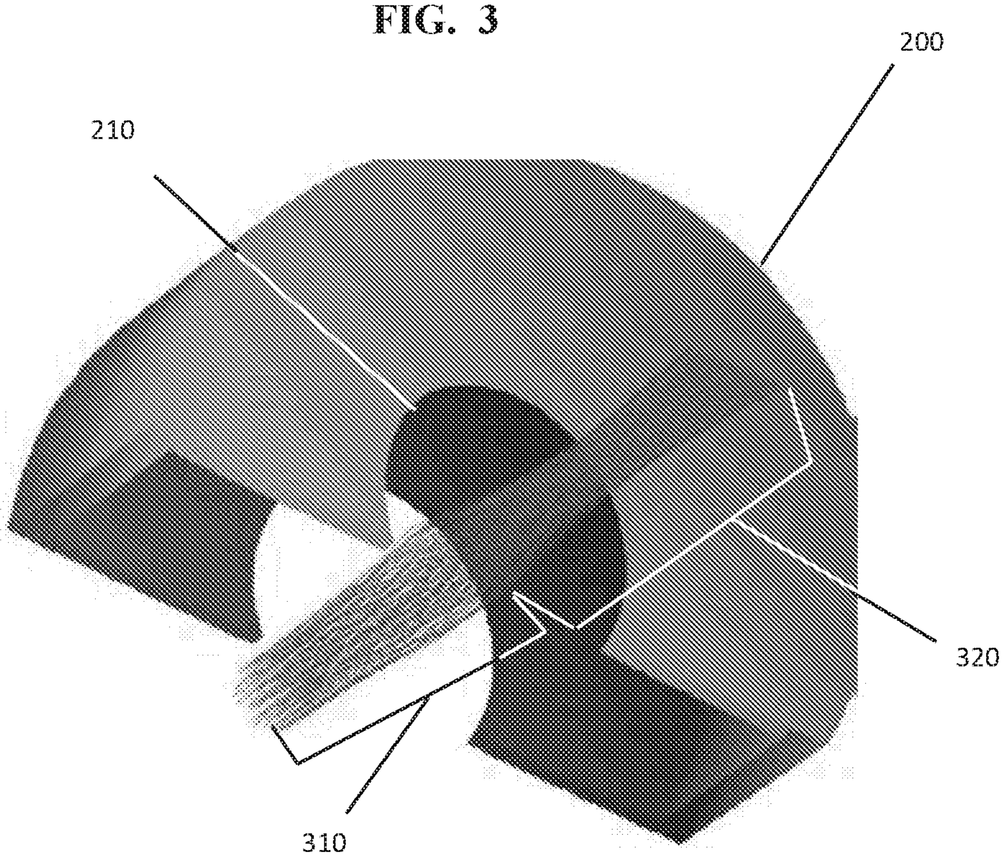
200
210
320
310

FIG. 4

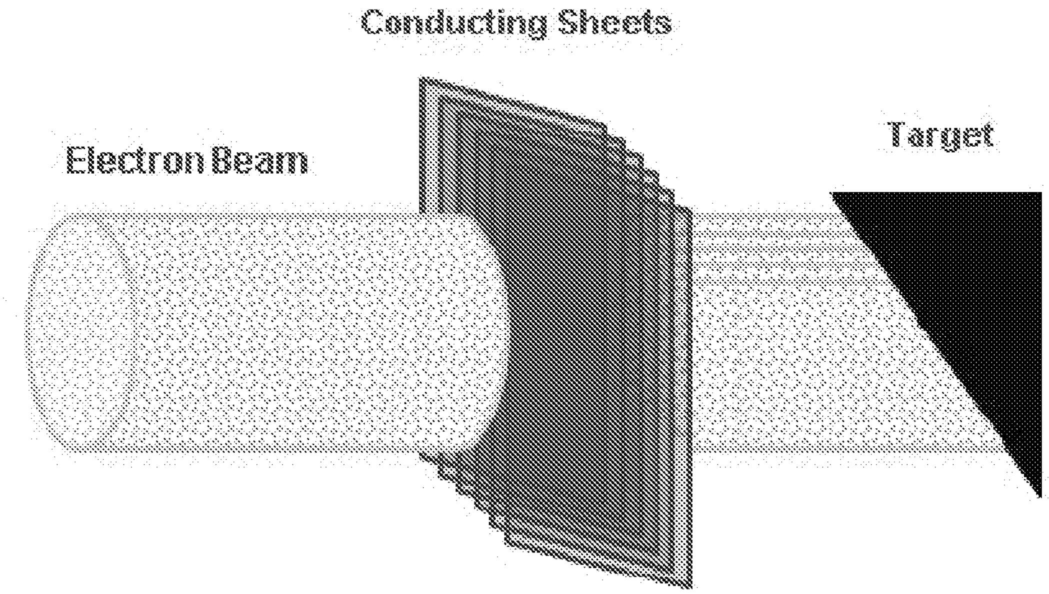
Conducting Sheets
Electron Beam
Target

FIG. 5A

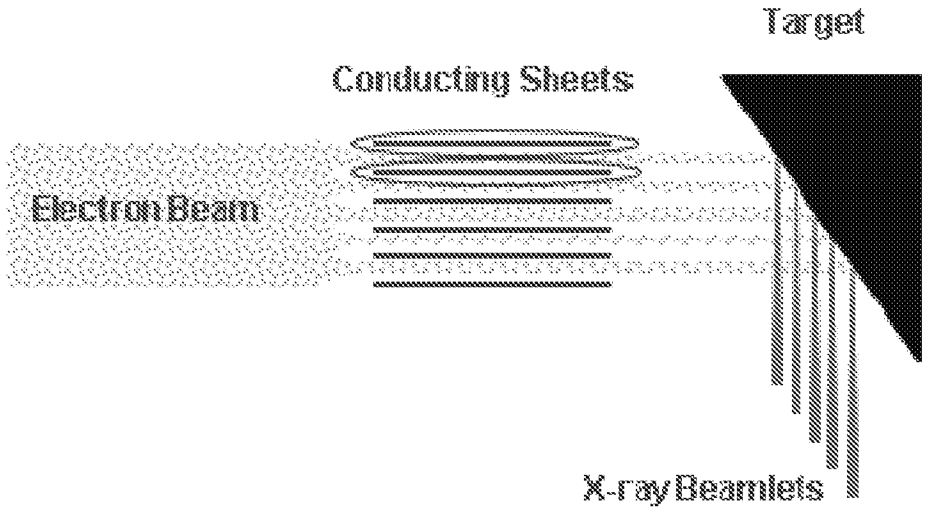
Target
Conducting Sheets
Electron Beam
X-ray Beamlets

FIG. 5B

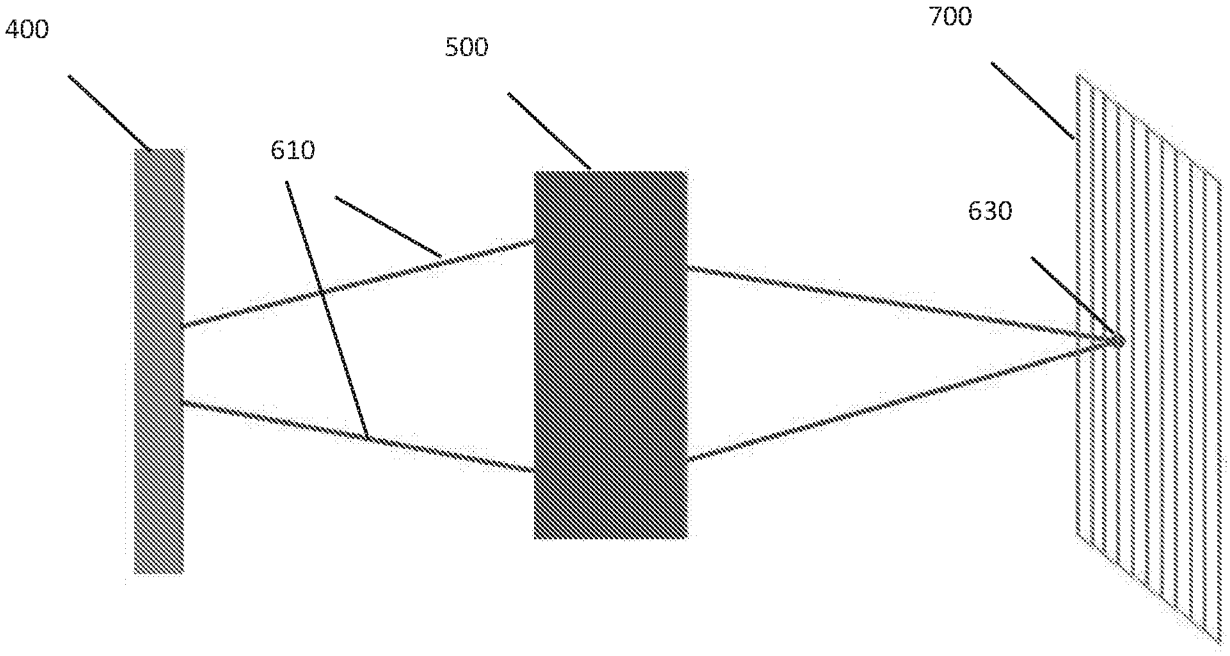

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/044287

A. CLASSIFICATION OF SUBJECT MATTER

H01J 35/04(2006.01)i, H01J 35/14(2006.01)i, A61B 6/00(2006.01)i, A61B 6/03(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01J 35/04; H01J 35/08; A61N 5/06; G01N 23/20; G01N 23/04; H05G 1/60; H01J 35/12; A61B 6/00; G21K 1/06; H01J 35/14; A61B 6/03

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: imaging system, X-ray source, source grating functionality

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2010-150136 A1 (KONINKLIJKE PHILIPS ELECTRONICS N. V. et al.) 29 December 2010 See page 2, lines 2-15; page 5, line 20 - page 6, line 16; claim 1; and figures 1-2.	1-5,7-10,28-35 ,38-42,50-55,66-69
Y		6,11-27,36-37 ,43-49,56-65
Y	US 2010-0080341 A1 (STEFAN POPESCU et al.) 01 April 2010 See paragraph [0042]; claims 1, 3, 7; and figure 2.	6,11-27,36-37 ,43-49,56-65
A	US 2005-0080466 A1 (GREGG S. HOMER) 14 April 2005 See paragraphs [0027], [0037]-[0045]; and figure 2.	1-69
A	WO 2014-125389 A1 (KONINKLIJKE PHILIPS N. V. et al.) 21 August 2014 See page 5, line 31 - page 7, line 15; claim 1; and figures 1-2.	1-69
A	US 2015-0071402 A1 (CANON KABUSHIKI KAISHA) 12 March 2015 See paragraphs [0028]-[0036]; and figures 1-2.	1-69

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 November 2016 (02.11.2016)	**02 November 2016 (02.11.2016)**

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2016/044287

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		DE 102008048688 B4	25/08/2011
		US 8009796 B2	30/08/2011
US 2005-0080466 A1	14/04/2005	CA 2535475 A1	28/04/2005
		EP 1680038 A2	19/07/2006
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		JP 2016-511924 A	21/04/2016
		US 2015-0380200 A1	31/12/2015
US 2015-0071402 A1	12/03/2015	JP 2015-072263 A	16/04/2015