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(54) MODULAR FABRICATION TECHNIQUE FOR GRATINGS FOR INTERFEROMETRIC X-RAY IMAGING

(57) A method of manufacture of a grating assembly (GA) from grating tiles for interferometric X-ray imaging and related devices to facilitate practicing the method. The method comprises applying (S350) a grating (GT) tile to a curved carrier substrate or applying the curved carrier substrate to the grating tile so that a curvature of the tile conforms with a curvature of the carrier substrate.

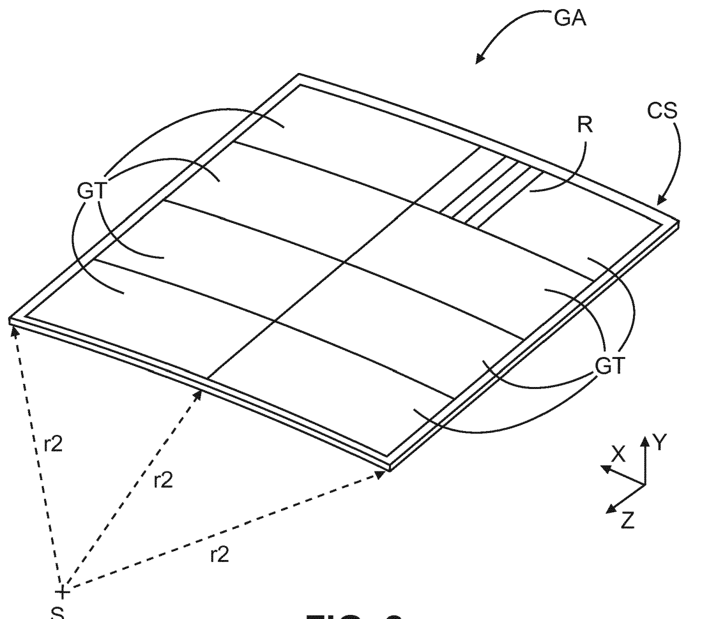

FIG. 2

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Description

FIELD OF THE INVENTION

[0001] The invention relates to a method of manufacture of a grating assembly, a grating assembly, a device for manufacturing of a grating assembly, a manufacturing system.

BACKGROUND OF THE INVENTION

[0002] Grating-based phase-contrast and dark-field x-ray (DAX) imaging is a promising technology to enhance diagnostic quality of x-ray equipment, eg, in areas of mammography, chest-radiography, and CT (computed tomography). As the name implies, grating-based imaging requires one or more (usually three) gratings as part of the imaging system. One such grating, commonly referred to as "G2", is situated between the patient and a detector of the imaging system.

[0003] One of the most challenging problems to build a clinical imaging system based on this technology is the manufacture of a full-field G2 grating. In particular, the relatively large area of an x-ray detector for chest examinations (almost 50 cm x 50 cm) is a big challenge as this needs to be covered completely by the G2 grating.

[0004] Currently, one of the more mature processes to build such gratings is the *LIGA* process. "*LIGA*" is a German acronym for "*Lithographie, Galvanoformung, Abformung*" (translatable into "lithography, electroplating, and molding"). In LIGA, the grating structures are fabricated from micrometer-sized gold structures onto graphite substrates. The maximum size of state of the art gratings is about 10 cm x 20 cm, due to a space-limited x-ray exposure system as well as wafer handling restrictions in the gold plating process used in the LIGA process.

[0005] The fabrication of large wafer sizes in one piece that are able to cover the x-ray detector completely is not currently available. Therefore, the current approach uses a "stitching" process to mount several small grating tiles together to cover the complete front face of an x-ray detector.

[0006] A further challenging in particular in DAX systems is the desire for focused gratings to reduce signal loss, in particular for large area imaging applications such as chest imaging. In such focused gratings, a cylindrical bending radius of the G2 grating is approximately 2-3 m. However, the individual grating wafers (which will be referred to herein a "grating tiles") are natively flat as made.

SUMMARY OF THE INVENTION

[0007] There may therefore be a need for alternative apparatus or system to improve manufacture of focused grating for imaging.

[0008] The object of the present invention is solved by the subject matter of the independent claims where further embodiments are incorporated in the dependent claims. It should be noted that the following described aspects of the invention equally applies to the device for manufacturing of a grating assembly, to the manufacturing system, to the computer program element, and to the computer readable medium.

[0009] According to a first aspect of the invention there is provided a method of manufacture of a grating assembly from grating tiles for interferometric X-ray imaging, comprising the step of:

applying a grating tile to a curved carrier substrate or applying the curved carrier substrate to the grating tile so that a curvature of the tile conforms with a curvature of the carrier substrate.

[0010] In embodiments, a thermal expansion coefficient of the carrier substrate corresponds to a thermal expansion coefficient of a grating substrate.

[0011] In embodiments, the carrier substrate includes glass or graphite.

[0012] The carrier substrate may be obtained by bending a heated glass sheet over a (positive) mold. The mold may be made from Aluminum or other metal or other non-metal material. Mold may be obtained with the required curvature through additive manufacturing, 3D print, CNC machining etc. A graphite carrier substrate may be obtained by CNC machining.

[0013] In embodiments, the glass is at least in part borosilicate glass.

[0014] In embodiments, the grating substrate includes graphite or silicon.

[0015] The material combinations of the carrier substrate and the grating substrate envisaged herein in include "glass (carrier substrate) on graphite (grating substrate)", "glass on silicon" or "graphite on graphite", or "graphite on silicon". Out of the with-glass combinations, glass on silicon may be preferred as one may find a glass material with suitably thermal expansion coefficient that matches silicon better than graphite. In embodiments, the method, comprises, prior to the applying step, a step of arranging the grating tiles on a curved surface of a manufacturing device.

[0016] In embodiments, the grating tiles are so arranged group-wise.

[0017] In embodiments, the arranging step includes aligning at least one of the grating tiles using a stop edge.

[0018] In embodiments, there is a gap between two neighboring grating tiles, the method further comprising reducing a width of such a gap.

[0019] In embodiments, the method comprises arranging a separator or sealing element in the said gap. This avoids glue entering the gap and causing unwanted adhesion of the tile(s) to a work surface.

[0020] In embodiments, the method comprises, prior to the applying step, dispensing X-ray compatible glue on the carrier or on one or more of the grating tiles.

[0021] The proposed method allows supporting efficient manufacture of in particular focused, large surface area gratings having a required bending radius. The method facilitates precise combination ("stitching") of individual grating tiles. Alignment of the grating tiles are preserved during manufacture. Complex and time consuming post-assemblage alignment checks and/or adjustment operations such as laser-based or other are no longer necessary with the proposed method.

[0022] In a further aspect, there is provided a grating assembly including a glass carrier with grating tiles deposited therein, obtainable through the method as per any one of the preceding claims.

[0023] In a further aspect there is provided a device for manufacturing a grating assembly from grating tiles, comprising:

a plurality of vacuum chucks having respective receiving segment surfaces for receiving one or more gratings tiles, the segment surfaces curved to together form a section of a lateral cylinder surface.

[0024] In embodiments, the vacuum chuck configured to exert vacuum suction on the respective gratings so as to bend and fix the respective grating tile to conform with the curvature of the respective curved segment surface.

[0025] In embodiments, the vacuum chucks are movable in a motion relative to each other so as increase or decrease a gap between the respective segment surfaces.

[0026] In embodiments, the motion is constrained to a lineal motion.

[0027] In embodiments, the lineal motion is so constrained such that, when a grating tile is fixed on a given segment surface, said motion is parallel to a longitudinal direction of ridges of the grating tile.

[0028] In embodiments, the device includes a stop edge as an aid to align a grating tile on at least one segment surface.

[0029] In embodiments, the stop edge is removably mountable on one of the segment surfaces, removable from said segment surface and mountable on a different one of the segment surfaces or in a different location of the said segment surface.

[0030] In a further aspect there is provided a manufacturing system, comprising a device as per any of one of the above described embodiment, further comprising an arm or a device with such an arm, configured to urge a curved carrier substrate and/or the grating tiles towards each other whilst the grating tiles are arranged on and held by the vacuum chucks, so that the grating tiles are sandwiched between the segment surfaces and the carrier substrate.

[0031] In a further aspect there is provided a control logic configured to perform a method as per any one of the above mentioned embodiments.

[0032] In a further aspect there is provided a computer program element, which, when being executed by at least one processing unit, is adapted to cause the processing unit to perform the method as per any one of the above mentioned embodiments.

[0033] In a further aspect there is provided a computer readable medium having stored thereon the program element.

[0034] In sum, what is proposed herein is a modular approach to mount and align several gratings into a combined, curved super-surface. In embodiments a mounting table is used that includes of plurality of preferably identically (or at least similar) shaped blocks or "segments". The segments, in embodiments a plurality of vacuum chucks, can be moved in one direction relative to each other with high precision. The geometrical tolerances of the individual segments and the tolerances between segments preferably less than 50 μm. The top surface, or receiving surface of each segment has a cylindrical surface with a bending radius that matches the required bending radius of the grating assembly to be manufactured. In embodiments, a vacuum pump system is connected to some or each segment. Vacuum can be applied and released to each individual grating tile, placed on top of the curved receiving surface of the mounting segment. The precise alignment of each grating tile relative to a given segment may be done by means of a stop edge. After placement of a single grating tile against the leading edge, the tile is fixed by activating the corresponding vacuum chuck. All segments are successively loaded with grating tiles while the leading edge is moved from one segment to another. In a last step, after removal of the stop edge, the movable segments each carrying one or more of the tiles are drawn together to so form a single combined curved surface of the G2 grating assembly, with gaps between individual tiles preferably less than 50μm.

[0035] The advantages of the proposed modular fabrication technique and of the supporting devices/systems as described herein to carry the method into practice include:

- individual grating tiles can be pre-aligned with high precision;
- use of the stop edge facilitates a parallel placement of individual grating tiles.
- fixation of individual grating tiles by vacuum is a versatile and non-destructive process;
- fixation of the grating tiles by vacuum during the curing time of the glue conserves alignment/orientation of the gratings;
- fixation of all grating tiles in one single glue step instead of individual gluing steps eliminates orientation/alignment errors;
- fixation of the grating matrix by glue to the supporting carrier substrate facilitates preserving orientation of the grating tiles;
- customization including replacing grating tile(s) at different sizes can easily be handled by adapting the segments of the vacuum table accordingly,
- automation of parts or the whole of the manufacturing method is possible, including any one or more (or all) of: placement of gratings, movement of the vacuum table segment, application of glue, application of the carrier substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0036] Exemplary embodiments of the invention will now be described with reference to the following drawings, which are not to scale, wherein:

Fig. 1 shows a schematic diagram of an interferometric x-ray imaging apparatus;
Fig. 2 shows a perspective view of a grating assembly assembled from grating tiles;
Fig. 3 shows a flow chart of a method of manufacturing a grating assembly;
Fig. 4 shows a manufacturing chain for manufacture of a grating assembly;
Figs. 5A-C show a device configured to facilitate assembly of a grating assembly;
Figs. 6A-D illustrate in plan view a step of arranging grating tiles on a work surface;
Figs. 7A-C illustrate in side elevation grating tiles arranged on a work surface of a device that facilitates manufacture of a grating assembly;
Fig. 8A illustrates, in plan view, a step of arranging a sealant in a system of grating tiles; and
Fig. 8B is a cross sectional view of a grating assembly with a sealant included.

DETAILED DESCRIPTION OF EMBODIMENTS

[0037] With reference to Fig. 1, this shows a schematic diagram of components of an interferometric x-ray imaging apparatus IA.

[0038] The apparatus IA includes an x-radiation source S and an x-radiation sensitive detector D. There is an examination region between the x-ray source and the detector D where the object to be imaged (not shown) usually resides during imaging.

[0039] The imaging apparatus IA further includes an interferometer IF. Thanks to the interferometer IF, at least a part of which is also arranged in the examination region between the source S and the detector D, the imaging apparatus is capable of providing not only absorption images, but also phase contrast and/or dark field images. The latter two have been found to provide additional diagnostic value. The latter two images harness different contrast mechanisms than absorption imaging, in that they allow imaging the amount of phase change or small angle scatter, respectively, as caused by the object to be imaged, eg patient tissue. For example, in the medical field as mainly envisaged herein, phase contrast imaging allows better imaging of soft tissue where contrast is usually too for absorption based imaging. Dark field images on the other hand have been found to provide good contrast for micro structures and may be hence be useful in the detection of early stages of breast cancer.

[0040] In embodiments, but not necessarily in all embodiments, the interferometer IF includes three grating structures referred to herein as "G0", the source grating, "G1", the phase grating, and "G2", the analyzer grating. The source grating G0 is optional and is used to produce coherent x-radiation at the source S. In other words, if the source S produces native coherent radiation, the grating G0 may not be required. The source grating G0 and the analyzer grating G2 are absorption gratings whilst the grating G1 is, as the name suggests, a phase grating.

[0041] In operation, x-radiation emanates from the source S, interacts with matter in the imaged object and the interferometer to cause a diffraction or a Moire pattern which can be detected at the detector D. Signal processing can then be used to analyze this pattern to compute dark field or phase contrast imagery and, if desired, conventional absorption imagery.

[0042] The gratings are in general oblong or square shaped and are preferably as shown in Fig. 1 focused towards the focal spot of the source. In other words, the gratings G0, G1 and G2 are curved, in particular, form respective sections of lateral surfaces of three imaginary concentric cylinders with radiuses r_0, r_1 and r_2, respectively. Having the gratings focused in this manner affords better signal efficiency. In Fig. 1, directions X,Z represent the two spatial dimensions of the gratings whilst direction Y is the imaging direction parallel to the optical axis OX of the system IA.

[0043] The imaging apparatus IA mainly envisaged herein is of the full view type in that the spatial dimension (when viewed in perspective view along the optical axis) of grating G2 corresponds to the shape and size of the radiation sensitive surface of the detector D. In certain applications envisaged herein, such as chest imaging, the detector and hence the G2 is quite large, up to 50 x 50cm2 or even larger for non-medical applications such as full body screeners. In other words, in full-view systems IA, the analyzer grating G2 has about the same size as the detector D. As mentioned earlier in the background, producing such full-view gratings in large sizes is not currently possible. Instead, the analyzer grating G2 needs to be assembled or "stitched" together from smaller grating tiles GT so as to build the analyzer grating G2 in the required size.

[0044] Manufacture of the grating tiles GT themselves are outside the scope of the present disclosure and has been described elsewhere in detail such as Mohr J et al in "High aspect ratio gratings for x-ray phase contrast imaging", published AIP Conf. Proc., vol. 1466, pp 41-50 (2012), and David C, et al in "Fabrication of diffraction gratings for hard x-ray phase contrast imaging", Microelectron. Eng., vol 84, pp 1172-7 (2007). Grating tiles GT for use in the context of the present disclosure can be currently obtained and are usually square or oblong shaped and have a thickness of about 1000 microns (in Y direction). As such, the grating tiles GT themselves are planar and include two surfaces, a proximal and a distal surface, the proximal being closer to the source S when in use along direction Y. The proximal surface of the grating tile may also be referred to herein as the "top surface" whilst the other, opposing, distal surface, as the "lower surface".

[0045] A grating tile GT includes a grating substrate or main body that has the upper and lower surface. The upper surface of the grating substrate is ruled to include a set of parallel rulings or grooves with ridges left between any two neighboring grooves. These grooves can be obtained by etching or lithographic techniques as previously described. In addition, the grooves are partly or fully filled with a high Z material such as gold or lead to so obtain a set of parallel grating lamellae of the grating tile GT. The grating substrate itself is made from a suitable material such as silicone or graphite.

[0046] The proposed manufacturing method, and related device, allow efficient production of curve grating assemblies from existing planar grating tiles to so build focused gratings, in particular absorption or phase gratings, of any desired size and or use in interferometric X-ray imaging.

[0047] One such grating assembly GA that can be built with the proposed method is shown schematically in Fig. 2. The grating example GA includes a plurality of grating tiles GT (8 in number in the example of Fig. 2) arranged in a matrix layout. The tiles GT have, in one direction, say X, their ruling patterns aligned in parallel and have, along the other direction, Z, their ruling patterns aligned in registry with each other, that is, groove at groove and ridge at ridge.

[0048] The grating tiles GT are fixed to a curved carrier substrate CS. In particular, the grating tiles are glued to the carrier substrate CS. The curvature of the carrier substrate CS corresponds to the required curvature of the imaginary lateral cylinder surface with radius r2. The carrier substrate CS with the glue (not shown) applied thereto forces the gratings to conform to the required curvature as the gratings themselves are naturally planar as mentioned earlier.

[0049] It is desirable to maintain the X,Z-alignment of the gratings' ruled surfaces during a range of operating conditions of the imaging apparatus. Applicant has found that this can be achieved by having a thermal expansion coefficient of the carrier substrate CS correspond, in particular equal, the thermal expansion coefficient of the grating substrate of the tiles GT. In particular, when the gratings tiles GT are from silicon or graphite, it is advantageous to have the carrier substrate CS made from glass, in particular pure glass. More specifically, a curved sheet of floating glass, or more particular borosilicate glass is used with a thermal expansion coefficient equaling that of graphite or silicone. Other material combinations for the carrier substrate and the grating substrate can be used provided that their thermal expansion coefficients are essentially equal or are within a tolerable range of each other.

[0050] The carrier substrate CS is, in embodiments, a curved glass sheet having the required curvature or bend radius of r2 with its size (area surface) and shape equaling (in perspective view along direction Y) the size and shape of the radiation sensitive surface of the detector D.

[0051] Reference is now made to the flow chart Fig. 3 which shows steps of the proposed method of manufacturing a grating assembly GA such as the one shown in Fig. 2. Whilst production of an analyzer grating G2 is mainly envisaged herein, the proposed principles can equally be applied to the source grating and/or the phase grating if required. Of main interest herein however is indeed the grating G2 as this is the largest of the gratings. It should be understood that use in a full-view imager is not necessarily required, and the grating assembly GA can still be used in grating-scanning systems when there is still a need for a larger grating structure.

[0052] As mentioned earlier, the proposed method allows efficiently assembling the grating assembly GA of any required size by combining or stitching together a required number of grating tiles in a matrix structure or layout. Initially, the grating tiles, each an absorbing grating in itself, is usually planar or of a natural curvature other than the required one of r2, and the grating tiles are in general of oblong or square shape. Other shapes are also envisaged herein. The grating tile are not necessarily all of the same shape and/or size.

[0053] Broadly, at step S310, the required number of grating tiles are arranged on a work surface. The work surface is such that it allows pre-bending and fixing the grating tiles from their natural planar shape into the required curvature r2

[0054] As will be explained in more detail below, the work surface may be formed by one or more surfaces of a segment, such as vacuum chucks of a vacuum assisted device, but any other work surface is also envisaged. The arranging of the tiles GT can be done group wise, one by one, or all or at once. Preferably, sub-modules are first formed by arranging a group of two or more gratings on the work surface the first step, and then in one or more follow-up steps other groups of grating tiles GT are so arranged. The tiles GT in each group may be applied one at a time or at once. Preferably, the grating tiles GT are applied face-down, or up-side-down, with the upper surfaces facing the work surface, leaving the lower surfaces exposed. A stop edge may be used to assist in aligning the gratings.

[0055] For efficient manufacturing, gaps may be left between the tiles GT, in particular in tiles of different groups, and these may be reduced in an optional step S320. Again, a specially designed tool may be used for this gap reduction. In one embodiment the gap reduction can be achieved by the vacuum chucks being moveable towards each other as will be explained more fully below.

[0056] At step S330, the remaining, now width-reduced, gaps are sealed off so that glue dispensed at a follow-up step S340 does not penetrate into the said gaps between the grating tiles. The glue is dispended pointwisely or in lines or otherwise on the fixed grating tiles. In particular, the glue is applied to the lower surface of the grating tiles as these may be held upside-down as mentioned earlier.

[0057] At step S350 the curved carrier substrate, made in embodiments from glass, is then applied to the pre-bent set of grating tiles arranged on the work surface. The curvature of the applied carrier substrate CS conforms with that of the gratings as held, and hence with the curvature of the work surface of the tool used to hold the grating tiles in position and under curvature. In other word, the carrier substrate CS's curvature mates with that of the work surface so as to sandwich the grating tiles GT thereinbetween.

[0058] Step S350 of applying the curved carrier substrate CS to the pre-bent grating tiles includes urging the carrier substrate into contact with the glue to couple or bond the carrier substrate CS with the grating tiles. Alternatively, the work surface with the grating tiles thereon can be moved and urged into contact with the stationary carrier substrate CS. Alternatively still, opposing motions is imparted to both, the carrier substrate and the grating tiles on the work surface, to couple them together.

[0059] In step S360 the glue is then allowed to cure. The glue should be chosen so that the curing process does not set in immediately but may extend over a certain timeframe that may allow, if required, in an optional step S370 to adjust the alignments of the grating tiles, if required. This optional alignment may be done for example under assistance of a laser beam which is projected on the manufactured grating tiles and adjustment is done by micrometer screws or otherwise so that a pre-defined diffraction pattern is obtained on a screen. However, for this purpose the assembled grating assembly GI will need to be lifted from the work surface to allow exposing it to the interrogating laser beam. In addition, or as an alternative, adjustment may be done by microscope-assisted. It has been observed however that the proposed method affords supreme accuracy and the alignment adjustment step is obsolete thus increasing throughput of the proposed method.

[0060] Once the glue is fully cured the grating assembly GA is ready for use. Preferably, and as mentioned, in the above described steps, the grating tiles are arranged upside down on the concavely (relative to plan view direction Y) curved work surface, that is, with the upper surface pointing towards the work surface SS. In other words, the glass CS is applied to the back of the gratings. Fixing the gratings upside down to the concave work surface ensures that the lamellae of the grating tiles are spread apart, as opposed to a compression if they were to be bent convexly, thus ensuring good focusing properties.

[0061] The glue that is used in step S340 is required to be x-ray compatible. In addition, a certain viscosity is desirable in the range of 2000-10000 mPa·s (cP).

[0062] Whilst some or all of the above mentioned steps can be carried out manually in an assembly line, an at least partial or full automation of the proposed method is also envisaged herein. In this regard, reference is now made to an at least partially automated manufacturing chain MC as diagrammatically shown in Fig. 4.

[0063] Broadly, the manufacturing chain MC includes the above mentioned tool with the curved work surface on which the grating tiles GT are arranged. This tool may be referred to herein as a vacuum table VT which will be explained in more detail below. The proposed method can be carried out by a single or a plurality of robotic devices that operate in concert under the guidance of a control logic CL as implemented on a processing unit PU such as a computing device.

[0064] The one more robotic devices may include a tile dispenser TD. The tile dispenser may include a suitable arm or delivery device A1 that arranges the tiles one by one, at once or preferably group-wise as explained above on the curved work surface of the vacuum table VT. The arm A1 may terminate in a suitable end effector that allows dispensing the grating tiles. Oh hand like, articulated structure maybe used a vacuum-based end effector.

[0065] In this embodiment, the curvature of the work surface of the vacuum table corresponds to the required curvature of the imaginary lateral cylinder surface of the intended imaging system IA, as mentioned above in relation to Fig. 1.

[0066] A glue dispenser GD robotic unit having a third delivery component A3, such as a robotic arm, is used to apply glue on the previously laid out grating tiles on the work surface of the vacuum table VT. Suitable end effectors for the glue dispenser GD include nozzles, possibly with a piezoelectric tip portion through which the glue is expelled. Other end effectors are also envisaged.

[0067] In the Fig. 4 embodiment, which is in schematic side view, the curvature of the vacuum table work surface is concave, with the concave carrier substrate CS (the curved glass sheet) applied from above by a carrier substrate dispenser CD. A "dual" embodiment or table VT and carrier substrate with vice versa curvatures are also envisaged in alternative embodiments. However, as mentioned above, bending the gratings upside down against a concave surface ensures a favorably spreading of the lamellae rather than a less favorable compression.

[0068] A further robotic unit, a carrier substrate dispenser CD, may include a delivery component such as a robotic arm A2 with a suitably formed end effector such as a suction cup that engages the curved carrier substrate CS and applies it from top by urging the carrier substrate onto the glue to couple same with the grating tiles arranged on the vacuum table VT. Once coupled, the art A2 releases the carrier substrate.

[0069] The carrier substrate may be obtained from a curved glass sheet formed into desired curvature by bending same over a positive mold in an oven or kiln OV at a suitable temperature. The mold may be formed as a metal block, such as an aluminum block, or clay block, preferably a graphite block, or otherwise, having an exposed surface with the required curvature over which the glass sheet, previously planar, is bent under the influence of heat. The term *"arm"* as used above in Fig. 4 for the automated manufacturing system MC is to be construed broadly and includes any device or part thereof, articulated or not, capable of performing any one, or more, or all of the above described steps or actions. Reference is now made to Figs. 5A-5C that show more details of the manufacturing aiding component, that is the vacuum table VT.

[0070] Fig. 5A is a schematic diagram of the vacuum table in side elevation along direction z, that is, along a longitudinal direction in which the lamellae/rulings of the gratings run, whilst Fig. 5B is a plan view along optical axis direction Y. Fig. 5C is another side elevation, with view direction perpendicular to the view direction of Fig. 5A.

[0071] The vacuum table includes a frame TB. A set of vacuum chucks VC=VC1-VC4 are slideably arranged on a sliding arrangement SI, preferably in a matrix layout. The vacuum chucks are blocks and form segments of the work surface. More specifically, the vacuum chucks VC1-4 include respectively receiving surfaces SS1 and SS2 which together form, in this embodiment the concave, work surface on which the grating tiles can be received. Only one such chuck VC1 is shown in Fig. 5A, obstructing view on the other chucks VC2-4 arranged in sequence behind chuck VC1, along view direction z that extends into the drawing plane of Fig. 5A.

[0072] Each vacuum chuck VC includes one or more suction ports SP1, SP2 formed in, and preferably flush with, the receive surfaces SS1, SS2. The suction ports SP1, SP2 are communicatively coupled via a set of, preferably flexible, conduits, such as hoses or tubes, with a vacuum pump VP. Upon application of a vacuum as administered by the vacuum pump VP, the individual gratings GT arranged on the receiving surfaces SS1, SS2 respectively, are fixed and forced into a curved shape by the vacuum suction force exerted through the suction ports SP1, SP2. Each individual grating tile is then held by one or more suction ports into position and in the required curved shape so as to be ready to receive the carrier substrate CS applied from above.

[0073] As shown in double arrows in Figs. 5B,C, the vacuum chucks VC1-4 are moveable so as to increase or decrease a gap between neighboring vacuum chucks VC1,VC2, and hence between the tiles GT, by sliding the chucks VC on the sliding arrangement SA. The sliding arrangement SA may be arranged as a set of rails or similar, along which the vacuum chucks are slideable. Sliding may be done automatically by a powered actuator, such as servo or stepper motor, or other motorized arrangement. Alternatively, the sliding may be effected manually by user through a suitable set of manual actuators, such as precision micrometer screws or otherwise. In each embodiment, manual or externally powered, the SA includes preferably a sufficiently fine gearing mechanism that allows reducing the gap in suitably small-steps to better manage approach and for more precise positioning. The motion of the vacuum chucks is suitably constrained to be lineal and preferably parallel to the course along which the rulings are run, In Fig. 5A, the rulings extend into the drawing plane. In other words, the motion of the vacuum chucks is constrained to direction z, the same direction as the rulings run as shown in Figs. 6.

[0074] In order to facilitate conversion of the vacuum table VT for the manufacture of grating assemblies GA with different curvature requirements $r' \neq r2$, in certain embodiments the chucks VC are removable and replaceable by a new set of chucks (not shown) having their receiving surfaces SS' (not shown) formed at a different (the now required) curvature *r'*. Quick connectors for connecting/re-connecting the conduits L to the suction ports SP of the new chucks may be provided in embodiments to yet further facilitate the conversion. Similar quick release mechanisms are envisaged in embodiments for coupling/decoupling the chucks into the slider SA and/or frame TB.

[0075] As mentioned earlier, preferably the gratings are applied group-wise with one, two or more applied to a giving receiving surface SS1 of a vacuum chuck VC1. A next group of tiles is then applied to another vacuum chuck VC2 for instance. Once applied and fixed by vacuum, neighboring chucks are set into motion using the sliding arrangement so as to now reduce a gap between the vacuum chucks and hence the gratings on the two vacuum chucks. This can be repeated until all of the grating tiles are suitably bent and spaced, with gaps reduced. For suitably aligning the gratings per vacuum chuck, a stop edge SE may be used. The edge SE may be fixedly arranged or is preferably removeably mounted and removable on and from each of the chucks VC1, VC2.

[0076] In more detail, in some (but not all) embodiments the stop edge SE is essentially bow shaped and curved to conform with the curvature of the receiving surfaces SS of the chucks VC. The stop edge SE allows aligning the grating tiles GT1,2 on a chuck VC1 in parallel. In the bow-shaped embodiment, the stop edge SE, when mounted, is raised against the receiving surfaces SS1, SS2 as shown in Fig. 5C. The stop edge SE allows aligning the gratings by urging the respective tile edge (preferably the longer tile GT1,2 edge) into abutment with and against the stop edge SE. The grating tiles are then fixed by application of the vacuum, at which point the stop edge SE may be removed and affixed to the next sliding vacuum chuck VC2, and so on. For instance, in some of the bow-shaped embodiments the stop edge includes pins that mate with holes in the receiving surfaces SS1 and SS2 of the vacuum chucks. In alternative, and preferred, embodiments, the stop edge SE is not mounted on the receiving surfaces SS1,SS2 so that more surface SS1, SS2 area is available. In such embodiments, the stop edge is not bow-shaped but may be formed as part of a rectangular plate that is affixed to one of the respective side surfaces (the ones that have z as a normal) of the respective chuck VC, with an upper edge of the plate not flush but raised against the respective (curved) edge of the respective vacuum chucks. This raised portion of the plate then forms the stop edge SE.

[0077] The stop edge SE can be either moved manually in manual assembly or the stop edge SE can be moved by action of a suitable end effector of the robotic arm of the tile dispenser TD as mentioned above in connection with Fig. 4. It is assumed herein that the grating tiles that have a sufficiently precise orthogonal shape. Furthermore, the orientation of the rulings is assumed be parallel to one edge of the tile GT, preferably its short edge. Application of the stop edge SE then guarantees sufficient alignment accuracy of all grating tiles and the parallel orientation of all rulings within $\pm 0.03°$.

[0078] Fig. 5B shows a plan view of the table VC's curved surface (curvature is not visible in this view), with two suction ports per vacuum chuck exposed. In the representation of Fig. 5B, the vacuum chucks have been moved so as to minimize the gap thereinbetween, thus forming the work surface as a smooth, concavely curved surface which is coupled against the carrier substrate CS from above thereby sandwiching the grating tiles therein between. The above described steps are now described and illustrated in more detail with reference to Figs. 6-8. Referring now first to Figs. 6A-D, these show, in plan view, more details of the tile arranging step and gap reducing step as mentioned above in connection with flow chart Fig. 3 and vacuum table VC of Fig. 5.

[0079] Specifically, as shown in plan view in Fig. 6A, two grating tiles G1, G2 are applied to the receiving surface SS1 of the first chuck VC1. These two (or more) grating tiles GT1,2 form the first group, or "sub-module". The group of gratings on the said chuck are aligned using the stop edge SE. There is also a small gap between tiles GT1, GT2 per chuck, and this gap is ensured by introducing a temporally introduced distance piece, a feeler gauge, for instance a foil of about 50 μm thickness, which is removed once two adjacent tiles GT1,2 have their (preferably short edge) correctly positioned and distanced.

[0080] Vacuum is now applied through suction ports SP1 (not shown in Fig. 6A because of the intervening grating tiles) to urge and fix the two gratings in shape and position, respectively. The same step is now repeated for follow-up gratings GT3, GT4 on the next chuck, in particular the neighboring chuck VC2 and so on until the whole surface of the vacuum table is laid out in grating tiles.

[0081] The embodiments in Fig. 6 shows 8 grating tiles being used but this will be understood as exemplary. In embodiments, a single grating tile is arranged per vacuum chuck or more than two are so arranged. In embodiments it may not be necessary that the same number of grating tiles is arranged on each vacuum chuck but that number may differ in embodiments. As can be seen in Fig. 6B, the stop edge SE is repositioned to now be affixed to the second vacuum chuck VC2 to facilitate aligning the next group of grating tiles GT3,4 on the second chuck VC2. The feeler gauge may be used to ensure correct inter-grating spacing, and so on for the remaining chucks. Once aligned and positioned, vacuum is applied to the second chuck VC2 to fix the grating tiles, and the stop edge SE/feeler gauge is removed.

[0082] Fig. 6C is an illustration of the gap reducing step where the sliding arrangement SA has been used to move two of the chucks with their tiles laid out there-on closer together to reduce the gap between the two groups of tiles GT1,2 and GT3,4. The gap reduction step can be done at the end, after the whole work surface has been laid out with grating tiles or it can be done step by step for each two neighboring vacuum chucks once the grating tiles have been laid out on their surfaces. Tiles GT1, GT3 on two neighboring chucks are so positioned that once two neighboring chucks VC1, VC2 are slid into abutment, the correct distance between opposing edges of the tiles GT1, GT3 across neighboring chucks VC1, VC2 is achieved.

[0083] Fig. 6D shows now all gaps reduced after drawing the vacuum chucks together as facilitated by the sliding arrangement SA. The example eight grating tiles GT1-GT8 are now arranged suitably spaced apart and aligned.

[0084] Figs. 7A-C

show further details of the arranging step where the gratings are pre-bent into the desired curvature by operation of the vacuum pump.

[0085] Fig. 7A shows a section of the vacuum table in side elevation with one vacuum chuck VC having arranged on its surface SS1 two grating tiles GT1 and GT2.

[0086] In Fig. 7B glue is applied to the grating tiles, either in dots or in lines, on each grating tile. As mentioned earlier, glue GL is preferably x-ray compatible so that it does not decompose upon x-ray exposure or decomposes only after a pre-defined lifetime of ten plus years or other pre-defined duty cycle.

[0087] v 7C shows the sub step of applying, in this case from atop the glass surface CS, mating the concave surface of the receiving surfaces SS1,SS2 of the vacuum chucks VC1,2. The curved glass surface CS is urged against the vacuum table so as to spread the glue to facilitate fixture. The amount of glue applied is precisely computed based on the viscosity and the size of the grating tiles and a thickness of a sealing component AT (see Fig. 8 below), to achieve a uniform spread of the glue on each grating tile. Preferably, each portion of glue applied to a respective grating tile should spread substantially throughout the entirety of the respective tile surface. The gradient of the curvature is taken into account when choosing the correct viscosity, as the glue, when applied will tend to flow in a direction from the grating tile edges to the center. The correct viscosity is preferable because, if the viscosity is configured too low, the glue will concentrate in the center of the grating tile (see Fig. 7A). However, if the viscosity is configured too high, the glue GL will not evenly distribute between gratings and the applied carrier substrate CS. Preferably, in embodiments, the glue is applied in form of several dots/blobs whose locations are determined to take into account the curvature of the grating tiles' (lower) surface and the viscosity of the glue.

[0088] In embodiments, the glue GL is applied in discrete quanta to form a preferably equidistant grid of blobs. The dispensing of the glue can be done in sequence or in parallel. Each glue blob, once applied, tends to flow and spread. If glue GL is applied in sequence, the viscosity, blob volume and timing ensures that, at the conclusion of the dispensing procedure, the blobs have not merged yet but still preferably form a discrete pattern, although the earlier applied blobs may have by now spread more than the once applied later. Only when the carrier substrate CS is applied and urged against the gratings tiles GT, will the blobs spread and merge to form a uniform glue layer that covers the tiling areas (less the footprint of the sealing component AT as discussed in Fig. 8 below).

[0089] The thermal expansion coefficient of the glue will be different from that of the carrier CS and grating tiles. However, this does not interfere adversely as the glue has been observed to form a "floating" buffer or cushion between the carrier CS and the gratings, thus avoiding misalignment that otherwise may be caused by certain temperature gradients. So as to avoid glue GL accidently spilling into the inter-tile gap between two adjacent grating tiles GT1,2, a sealing component AT is applied in the mentioned sealing step. In this step, a sealing material, such as an adhesive tape, is applied prior to the administration of the glue so as to seal off the inter-grating tile gaps and preferably also the outer most edges of the grating tile assembly as shown in plan view in Fig. 8A.

[0090] The adhesive type is preferably made from polyimide, for instance Kapton ™ and is, in exemplary embodiments, about 50 μm thick and about 6-10 mm wide. Other dimensional measurements are also envisaged in other embodiments.

[0091] Side elevation Fig. 8B shows a system of adhesive tape AT applied to prevent leakage of glue onto the work surface of the chucks. Particularly, leakage of glue into the inter-tile spacing or beyond the outer edge of the assembly is prevented.

[0092] It is proposed herein to leave the adhesive tape in place as shown in Fig. 8B, in other words, the adhesive tape pattern forms an integral part of the ready grating assembly GA and the thickness of the adhesive tapes defines the gap to be filled by the glue. Referring back to the manufacturing chain in Fig. 4, it will be understood that some or all steps maybe done by a single, two or more than three robot units. For clarity, in Fig. 4, each step has been shown by a dedicated robot unit to be performed but this may not necessarily be so and some robotic units may perform more or one manufacturing step. The control logic CL may be arranged on a central computer but may also be arranged across a network of more than one computers. The control logic may be arranged in dedicated, hard-wired or programmable microprocessor arranged at the respective robotic unit. The respective control logics of each robotic unit may communicate through a suitable network infrastructure to synchronize the operating steps.

[0093] In another exemplary embodiment of the present invention, a computer program or a computer program element is provided that is characterized by being adapted to execute the method steps of the method according to one of the preceding embodiments, on an appropriate system.

[0094] The computer program element might therefore be stored on a computer unit, which might also be part of an embodiment of the present invention. This computing unit may be adapted to perform or induce a performing of the steps of the method described above. Moreover, it may be adapted to operate the components of the above-described apparatus. The computing unit can be adapted to operate automatically and/or to execute the orders of a user. A computer program may be loaded into a working memory of a data processor. The data processor may thus be equipped to carry out the method of the invention. This exemplary embodiment of the invention covers both, a computer program that right from the beginning uses the invention and a computer program that by means of an up-date turns an existing program into a program that uses the invention.

[0095] Further on, the computer program element might be able to provide all necessary steps to fulfill the procedure of an exemplary embodiment of the method as described above. According to a further exemplary embodiment of the present invention, a computer readable medium, such as a CD-ROM, is presented wherein the computer readable medium has a computer program element stored on it which computer program element is described by the preceding section.

[0096] A computer program may be stored and/or distributed on a suitable medium (in particular, but not necessarily, a non-transitory medium), such as an optical storage medium or a solid-state medium supplied together with or as part of other hardware, but may also be distributed in other forms, such as via the internet or other wired or wireless telecommunication systems. However, the computer program may also be presented over a network like the World Wide Web and can be downloaded into the working memory of a data processor from such a network. According to a further exemplary embodiment of the present invention, a medium for making a computer program element available for downloading is provided, which computer program element is arranged to perform a method according to one of the previously described embodiments of the invention.

[0097] It has to be noted that embodiments of the invention are described with reference to different subject matters. In particular, some embodiments are described with reference to method type claims whereas other embodiments are described with reference to the device type claims. However, a person skilled in the art will gather from the above and the following description that, unless otherwise notified, in addition to any combination of features belonging to one type of subject matter also any combination between features relating to different subject matters is considered to be disclosed with this application. However, all features can be combined providing synergetic effects that are more than the simple summation of the features.

[0098] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive. The invention is not limited to the disclosed embodiments. Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing a claimed invention, from a study of the drawings, the disclosure, and the dependent claims.

[0099] In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. A single processor or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are re-cited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope.

Claims

1. Method of manufacture of a grating assembly from grating tiles for interferometric X-ray imaging, comprising the step of:
applying (S350) a grating tile to a curved carrier substrate or applying the curved carrier substrate to the grating tile so that a curvature of the tile conforms with a curvature of the carrier substrate.

2. Method of claim 1, wherein a thermal expansion coefficient of the carrier substrate corresponds to a thermal expansion coefficient of a grating substrate.

3. Method of claim 1 or 2, wherein the carrier substrate includes glass.

4. Method of claim 3, wherein the glass is at least in part borosilicate glass.

5. Method of any one of the preceding claims, wherein the grating substrate includes graphite or silicon.

6. Method of any one of the preceding claims, comprising, prior to the applying step (S350), arranging (S310) the grating tiles on a curved surface of a manufacturing device.

7. Method of claim 6, wherein the arranging step (S310) includes aligning at least one of the grating tiles using a stop edge (SE).

8. Method of any one of the preceding claims, wherein there is a gap between two neighboring grating tiles, the method further comprising reducing (S320) a width of such a gap.

9. Method of any one of the preceding claims, comprising, prior to the applying step (S350), dispensing (S340) X-ray compatible glue on the carrier or on one or more of the grating tiles.

10. A grating assembly including a glass carrier with grating tiles deposited therein, obtainable through the method as per any one of the preceding claims.

11. A device (VT) for manufacturing a grating assembly from grating tiles, comprising:
a plurality of vacuum chucks (VC1, VC2) having respective receiving segment surfaces (SS1, SS2) for receiving one or more gratings tiles (GT1,GT2), the segment surfaces curved to together form a section of a lateral cylinder surface.

12. Device of claim 11, the vacuum chuck configured to exert vacuum suction on the respective gratings so as to bend and fix the respective grating tile to conform with the curvature of the respective curved segment surface.

13. Device of claim 11 or 12, wherein the vacuum chucks are movable in a motion relative to each other so as increase or decrease a gap between the respective segment surfaces.

14. Device of any one of claims 11-13, including a stop edge (SE) as an aid to align a grating tile on at least one segment surface.

15. A manufacturing system (MC), comprising a device as per any of claims 11-14, and an arm (A) configured to urge a curved carrier substrate and/or the grating tiles towards each other whilst the grating tiles are arranged on and held by the vacuum chucks, so that the grating tiles are sandwiched between the segment surfaces and the carrier substrate.

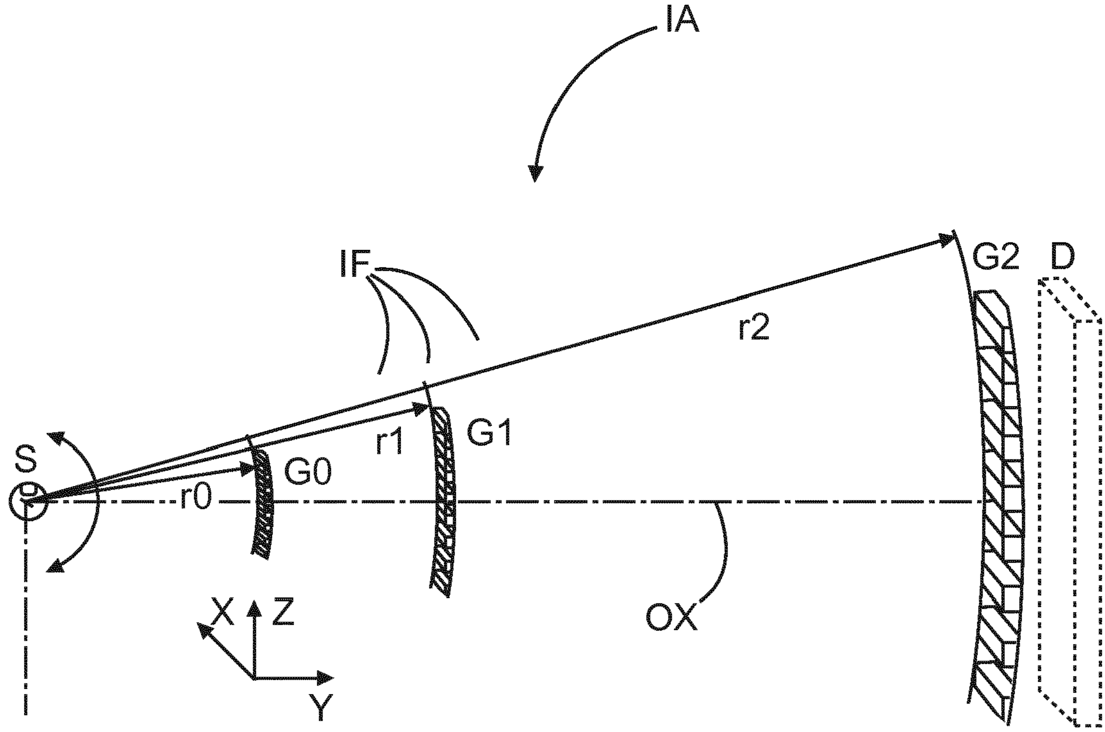

FIG. 1

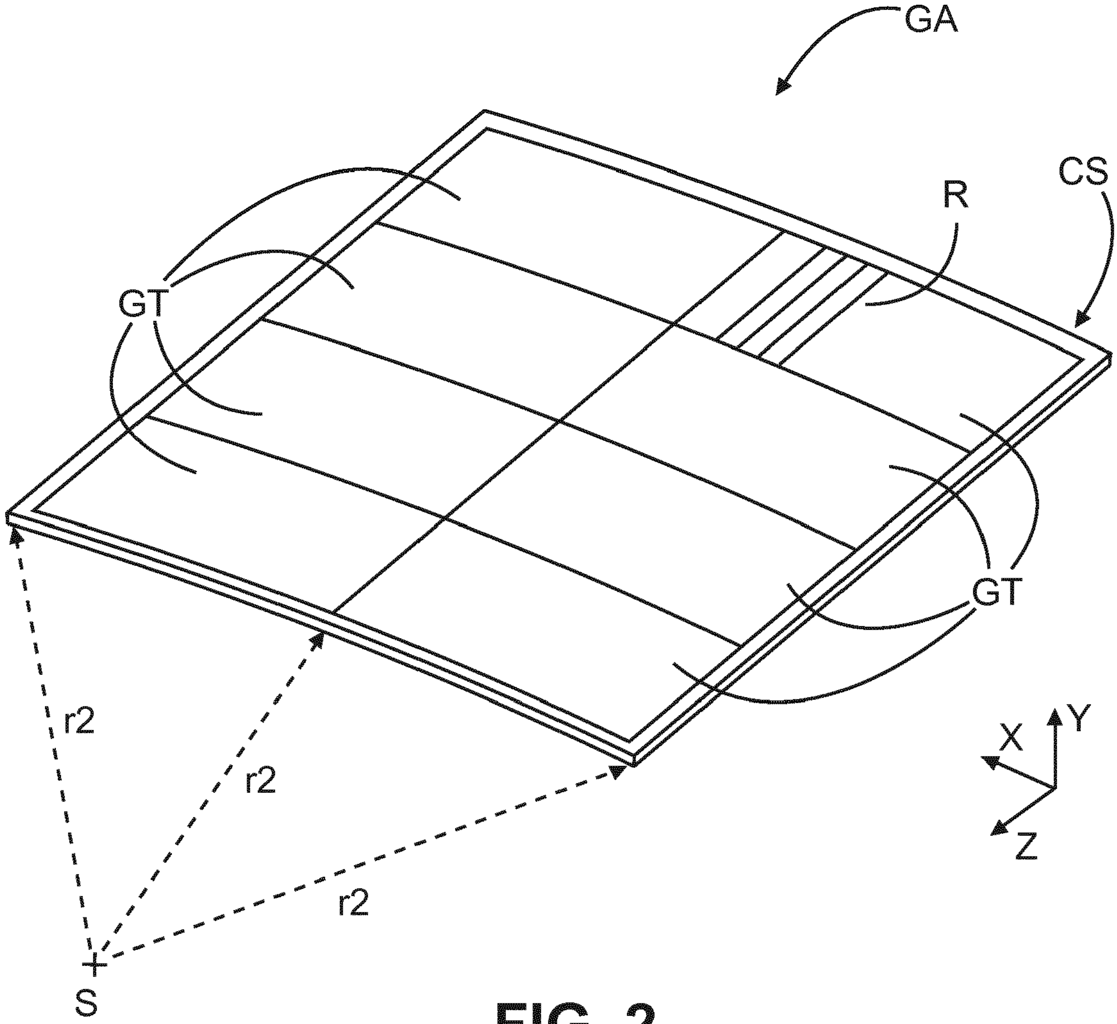

FIG. 2

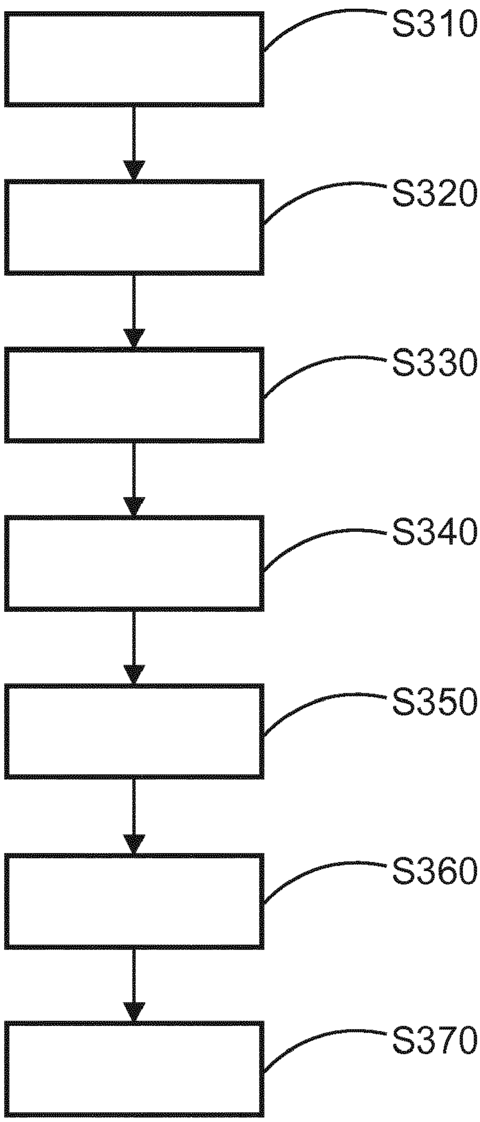

FIG. 3

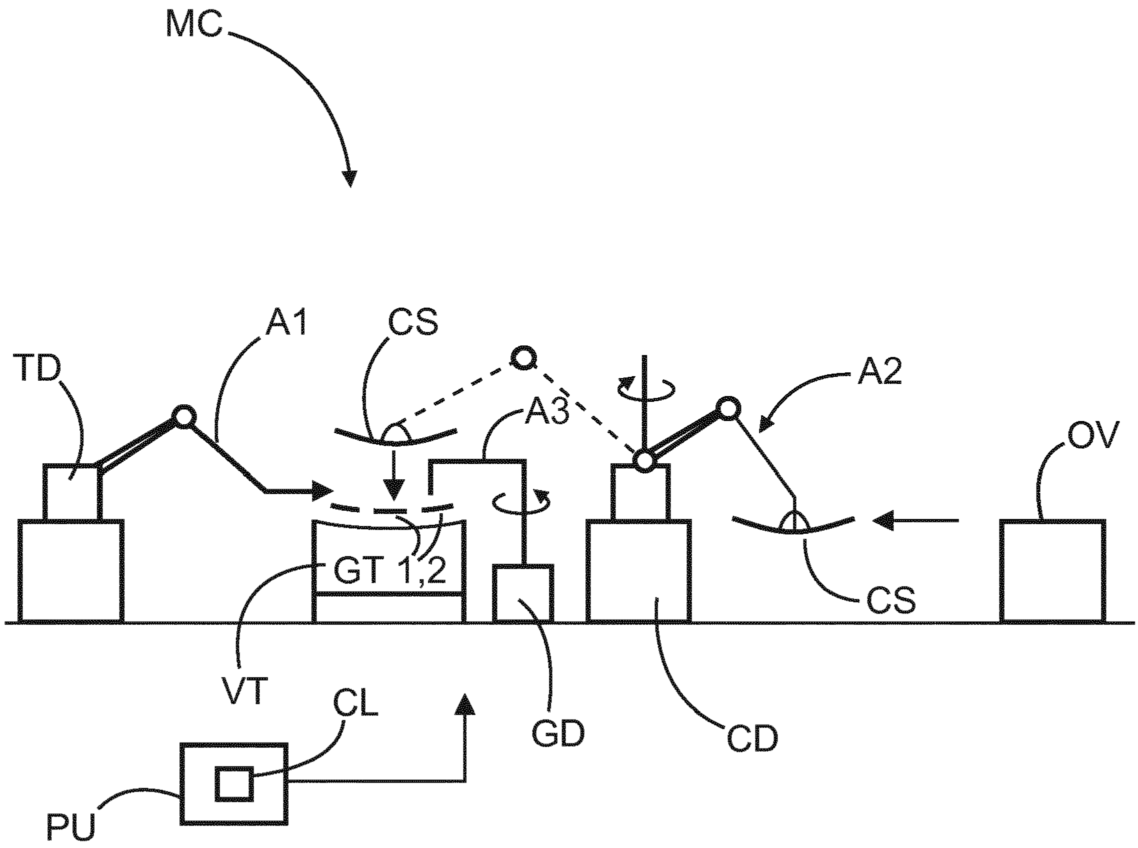

FIG. 4

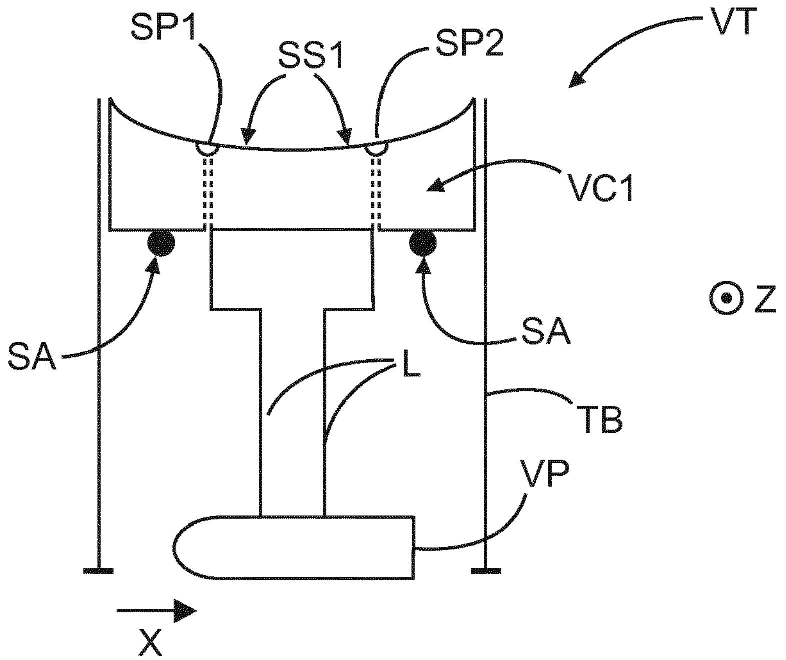

FIG. 5A

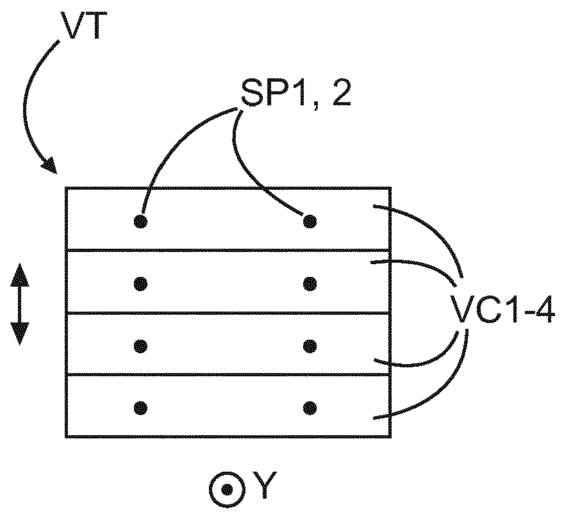

FIG. 5B

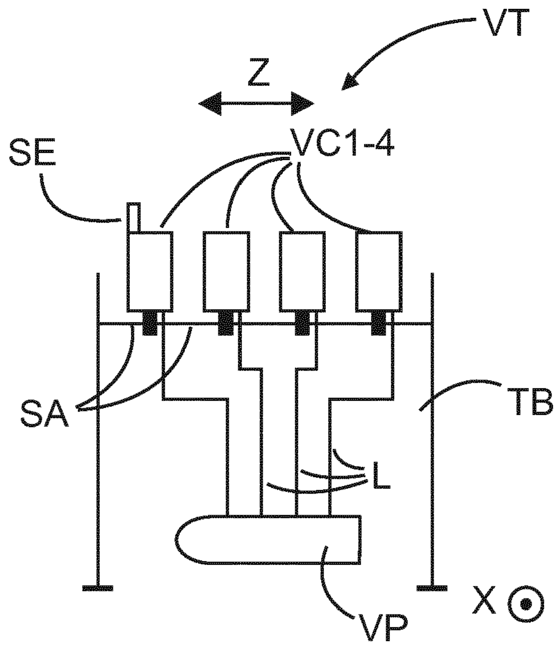

FIG. 5C

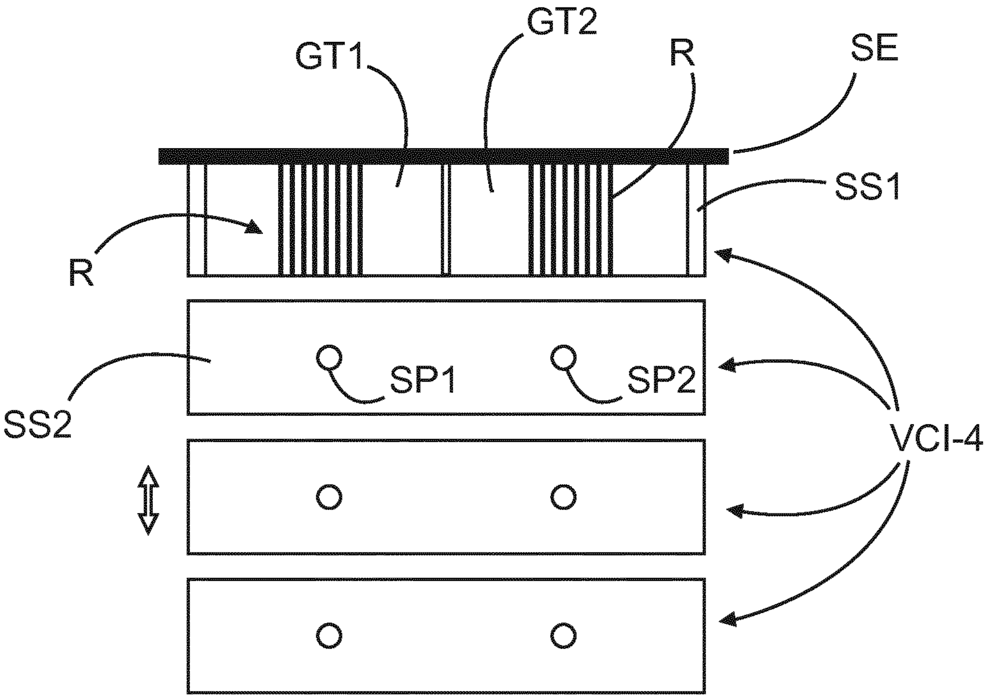

FIG. 6A

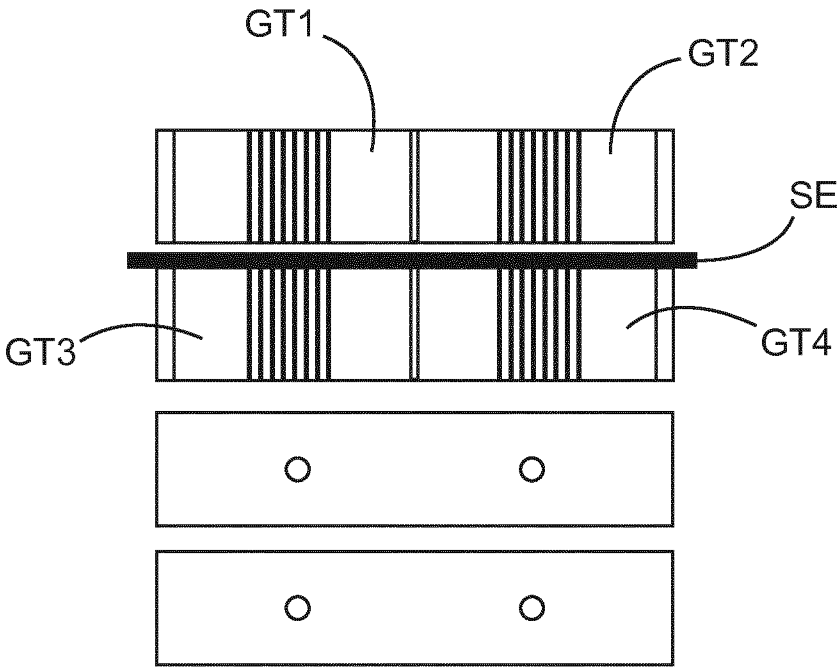

FIG. 6B

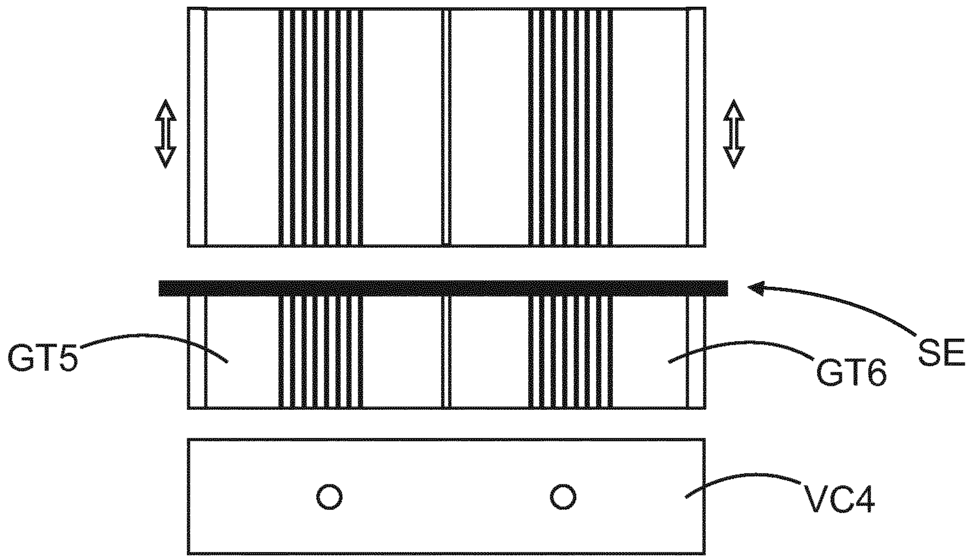

FIG. 6C

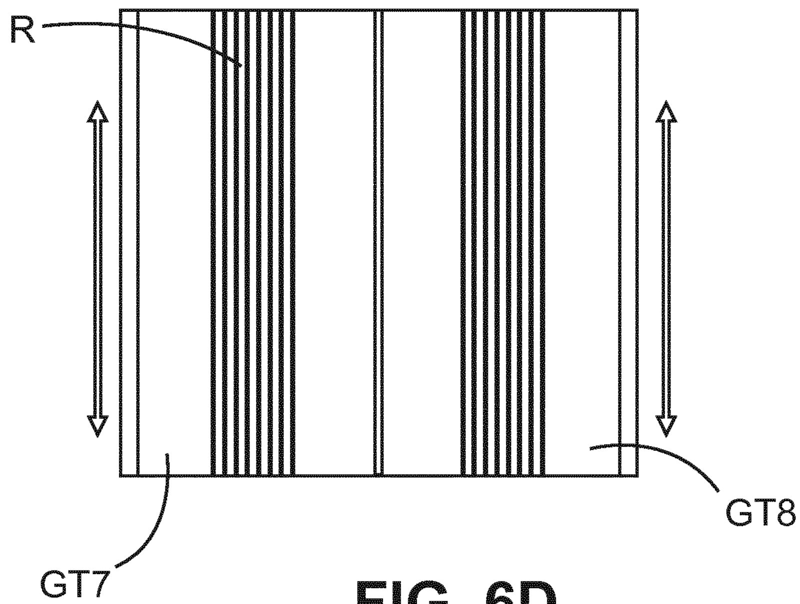

FIG. 6D

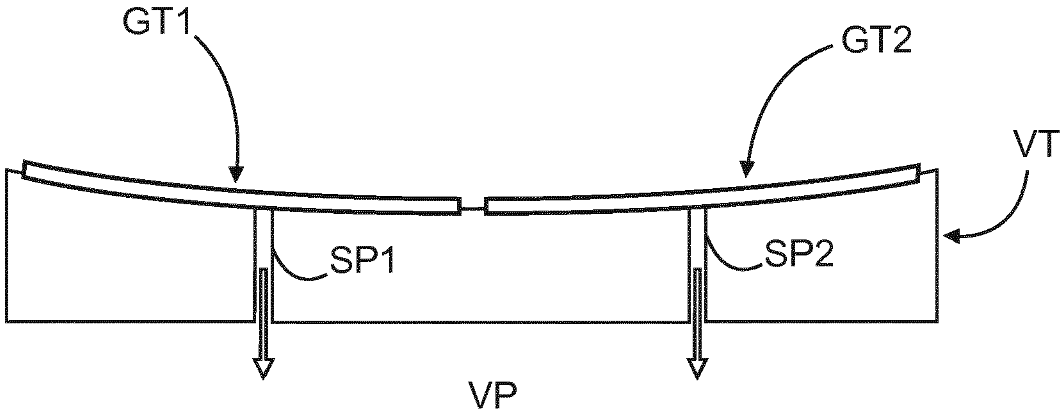

FIG. 7A

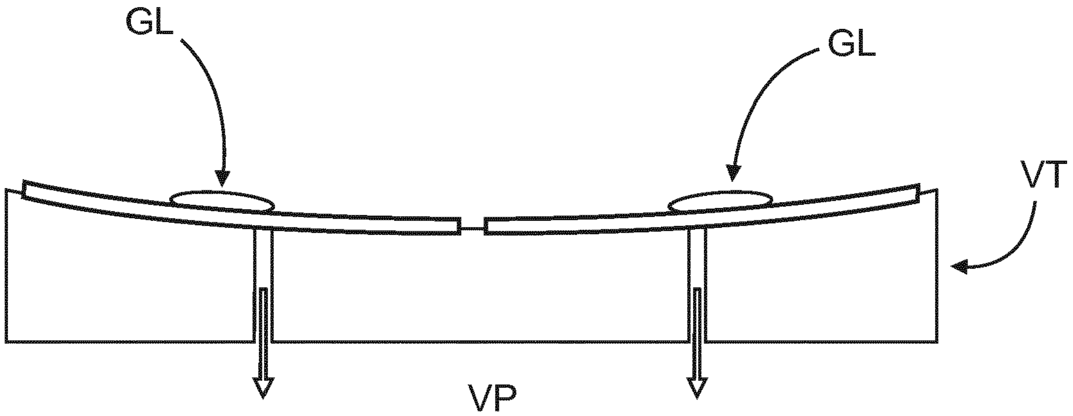

FIG. 7B

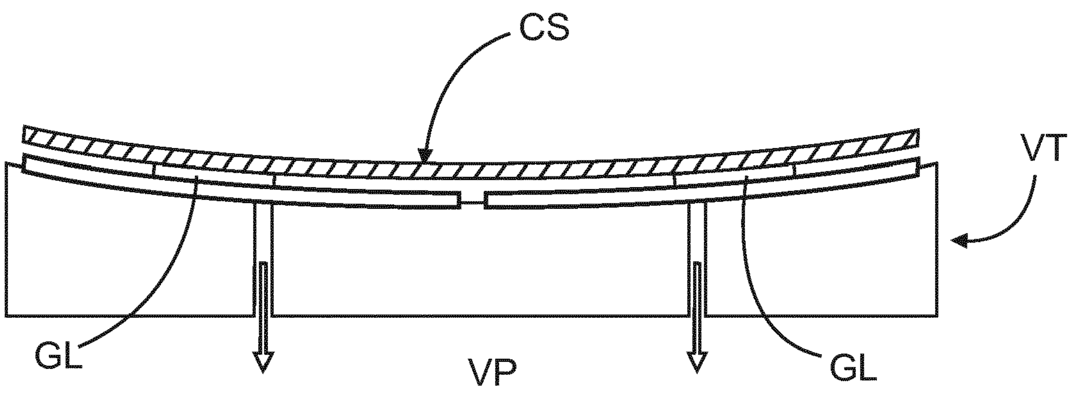

FIG. 7C

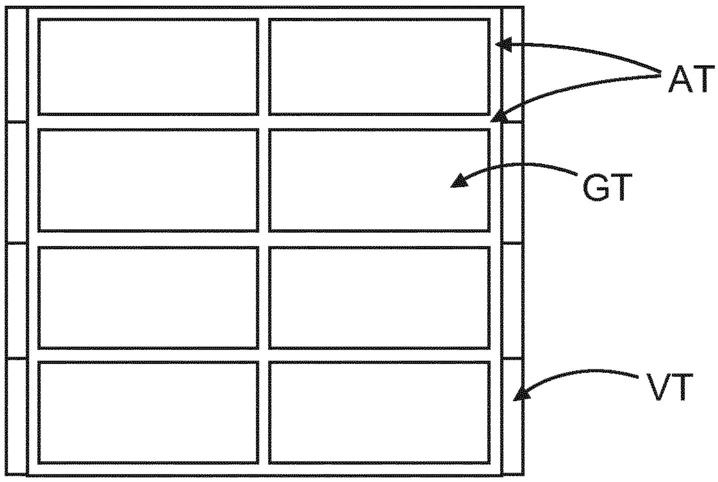

FIG. 8A

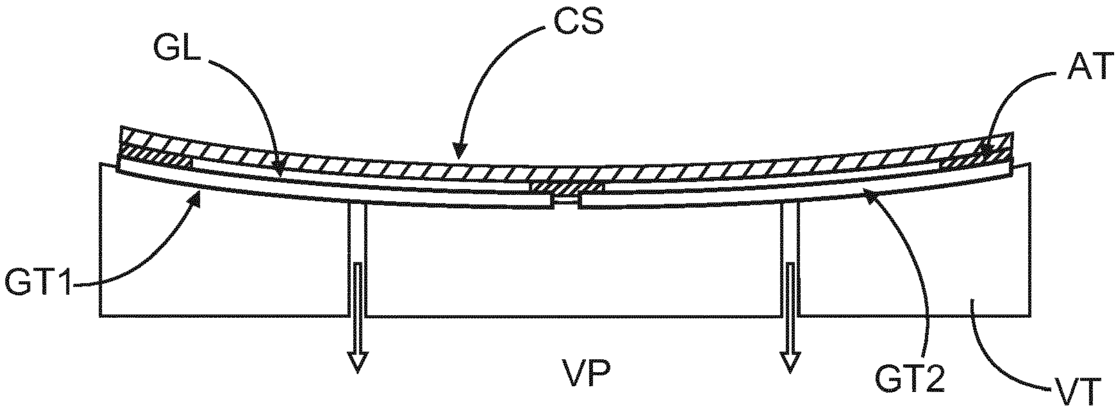

FIG. 8B

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EUROPEAN SEARCH REPORT

Application Number
EP 19 21 0859

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	EP 3 403 581 A1 (KONINKLIJKE PHILIPS NV [NL]; SCHERRER INST PAUL [CH]) 21 November 2018 (2018-11-21) * figures 2,3 * * paragraphs [0044], [0045] * * paragraphs [0053] - [0058] * * paragraph [0065] - paragraph [0068] * * paragraphs [0076], [0084], [0086], [0087] * * paragraph [0095] * -----	1,9	INV. G21K1/02 G21K1/06
X Y	US 2012/002785 A1 (KANEKO YASUHISA [JP]) 5 January 2012 (2012-01-05) * figures 7-12,23 * * paragraph [0010] - paragraph [0021] * * paragraph [0069] - paragraph [0074] * * paragraph [0079] - paragraph [0096] * * paragraphs [0099], [0103], [0104], [0105] * -----	1-3,5-7, 10 4	
Y	WO 2013/129308 A1 (FUJIFILM CORP [JP]) 6 September 2013 (2013-09-06) * paragraphs [0047], [0073]; figure 12 * -----	4	TECHNICAL FIELDS SEARCHED (IPC)
			G21K
A	KOCH F J ET AL: "Note: Gratings on low absorbing substrates for x-ray phase contrast imaging", REVIEW OF SCIENTIFIC INSTRUMENTS, AIP, MELVILLE, NY, US, vol. 86, no. 12, 28 December 2015 (2015-12-28), XP012211146, ISSN: 0034-6748, DOI: 10.1063/1.4939055 [retrieved on 1901-01-01] * the whole document * -----	5	

7

~~The present search report has been drawn up for all claims~~

Place of search	Date of completion of the search	Examiner
Munich	20 May 2020	Giovanardi, Chiara

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons
& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

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Application Number

EP 19 21 0859

CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing claims for which payment was due.

☐ Only part of the claims have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due and for those claims for which claims fees have been paid, namely claim(s):

☐ No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due.

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

☐ All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

☐ As all searchable claims could be searched without effort justifying an additional fee, the Search Division did not invite payment of any additional fee.

☐ Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:

☒ None of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:

1-7, 9, 10

☐ The present supplementary European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims (Rule 164 (1) EPC).

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LACK OF UNITY OF INVENTION SHEET B

Application Number
EP 19 21 0859

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

1. claims: 1-7, 9, 10

Method of manufacture of a grating assembly from grating tiles for interferometric X-ray imaging, comprising the step of: applying a grating tile to a curved carrier substrate or applying the curved carrier substrate to the grating tile so that a curvature of the tile conforms with a curvature of the carrier substrate.

1.1. claims: 1, 2

a thermal expansion coefficient of the carrier substrate corresponds to a thermal expansion coefficient of a grating substrate

1.2. claims: 3-7, 9, 10

the carrier substrate includes glass, optionally the glass is at least in part borosilicate glass

---

2. claim: 8

Method of manufacture of a grating assembly from grating tiles for interferometric X-ray imaging, comprising the step of: applying a grating tile to a curved carrier substrate or applying the curved carrier substrate to the grating tile so that a curvature of the tile conforms with a curvature of the carrier substrate; wherein there is a gap between two neighboring grating tiles, the method further comprising reducing a width of such a gap.

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3. claims: 11-15

A device for manufacturing a grating assembly from grating tiles, comprising: a plurality of vacuum chucks having respective receiving segment surfaces for receiving one or more gratings tiles, the segment surfaces curved to together form a section of a lateral cylinder surface.

Please note that all inventions mentioned under item 1, although not necessarily linked by a common inventive concept, could be searched without effort justifying an additional fee.

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 19 21 0859

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

20-05-2020

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EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

- **MOHR J et al.** High aspect ratio gratings for x-ray phase contrast imaging. *AIP Conf. Proc.,* 2012, vol. 1466, 41-50 **[0044]**
- **DAVID C et al.** Fabrication of diffraction gratings for hard x-ray phase contrast imaging. *Microelectron. Eng.,* 2007, vol. 84, 1172-7 **[0044]**