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(71) **Applicant**: **CANON KABUSHIKI KAISHA** [JP/JP]; 30-2, Shimomaruko 3-chome, Ohta-ku, Tokyo, 1468501 (JP).

(72) **Inventor**: **HANDA, Soichiro**; c/o CANON KABUSHIKI KAISHA, 30-2, Shimomaruko 3-chome, Ohta-ku, Tokyo, 1468501 (JP).

(74) **Agents**: **SERA, Kazunobu** et al.; Acropolis 21 Building 6th floor, 4-10, Higashi Nihonbashi 3-chome, Chuo-ku, Tokyo, 1030004 (JP).

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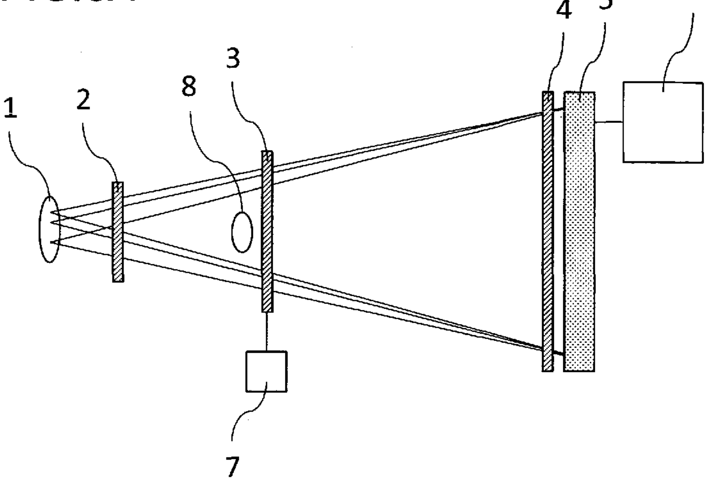
(54) **Title**: X-RAY IMAGING SYSTEM

FIG.3A



(57) **Abstract**: An X-ray imaging system comprises: a source grating configured to convert each micro X-ray source of a micro X-ray source array into a plurality of even smaller X-ray sources; a beam splitter grating configured to diffract an X-ray having passed through the source grating and to form an interference pattern; an analyzer grating configured to have a pattern for forming moire with the interference pattern; and an X-ray detector configured to image the moire formed between the interference pattern and the pattern of the analyzer grating.

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DESCRIPTION

Title of Invention

X-RAY IMAGING SYSTEM

Technical Field

[0001] The present invention relates to an X-ray imaging system.

Background Art

[0002] An imaging method for observing the internal structure of an object by detecting the X-ray transmittance distribution of the object has been widely used. Recently research and development on techniques to perform imaging by detecting phase shift distribution when an X-ray passes through an object are ongoing. A Talbot interferometry is one such technique.

[0003] In the Talbot interferometry, imaging is performed by detecting an interference pattern generated by an X-ray that has passed through an object and a beam splitter grating using an analyzer grating and an X-ray detector. According to the phase shift distribution of the X-ray that has passed through the object, more specifically, according to the refraction of the X-ray that has passed through the object, the interference pattern is distorted. This means that the phase distribution of the X-ray that has passed through the object can be acquired by analyzing the imaged pattern.

[0004] In order to acquire an interference pattern in the Talbot interferometry, an X-ray having high coherence must be used, therefore an X-ray source formed by a high power X-ray tube, of which effective size is several hundred μm or more, for example, cannot be used directly for the X-ray source here.

[0005] Therefore Patent Literature 1 proposes a method of installing another grating at the upstream side of the beam splitter grating. This additional grating may be called "source grating" in this description. The source grating is constituted by X-ray transmitting portions which are formed as lines or dots, and X-ray shielding portions. Since the width of a linear X-ray transmitting portion or the diameter of a point-like X-ray transmitting portion on the source grating is sufficiently small, the X-ray that has passed through the individual X-ray transmitting portion can have high coherence, and can generate an interference pattern by the beam splitter grating. Further, the X-ray transmitting portions are arranged according to a predetermined sequence, hence the interference pattern generated by an X-ray that has passed through these portions overlap with each other in a positional relationship with a displacement that has a multiple pattern period (pitch). Thereby the interference pattern can be acquired even if the size of the X-ray source is large. A Talbot interferometer that uses such a source grating may be called a "Talbot-Lau interferometer".

[0006] As another solution, Patent Literature 2 proposes a method of using a coded source imaging method.

According to the coded source imaging method, the shape of the X-ray source is controlled, whereby the point spread function (PSF) of the imaging system is controlled and the spatial resolution of the imaging system is improved ([see] Non-patent Literature 1). The effect of the PSF control in the coded source imaging method can be evaluated by a modulation transfer function (MTF), which is the absolute value of the Fourier transform of a PSF. In this description, it is assumed that a value used for MTF has been normalized, regarding the value at the origin of frequency coordinates as 1. An object image that is convoluted by a distinctive PSF, that is, used in the coded source imaging method, is an image that cannot be used directly, therefore normally some deconvolution processing is performed, and the final object image is acquired. This deconvolution processing in the coded source imaging method may be called "decoding processing". In the Talbot interferometer, the image forming steps are more complicated than normal X-ray imaging, but the principle of the coded source imaging method can be used with approximation.

[0007] The shape of the X-ray source that is normally used for the coded source imaging is a set of many micro

X-ray sources. This X-ray source can be obtained by using an X-ray shielding mask that has many micro-pinholes, for example. This X-ray shielding mask that has many micro-pinholes may be called a "coded aperture mask".

[0008] The above mentioned Patent Literature 2 proposes a method of using a coded aperture mask instead of the source grating proposed in Patent Literature 1, whereby MTF during interference pattern generation is increased based on the principle of the coded source imaging method and information on an interference pattern is transferred. Critical here is that the MTF reflects the influence that the shape of the coded source generates on the interface pattern generation of the analyzer grating, due to the effect of the so called "geometric unsharpness". In a Talbot interferometer, an interface pattern is often converted into a moire that is generated with the analyzer grating, and is detected by a detector, which has no spatial resolution to acquire an interference pattern directly. In this case, in an image that is finally detected, a certain amount of high frequency components, including the fundamental frequency components of the interference pattern, have been lost. To be precise, the MTF disclosed in Patent Literature 2 document is different from the MTF associated with an entire imaging system.

[0009] Generally speaking it is preferable in the Talbot interference method that an object and the beam splitter grating are close to each other. It is also preferable that the positions of the object and the beam splitter grating and the position of the analyzer grating are distant from each other by several hundred mm or more. Therefore normally the object and the X-ray detector are distant from each other by several hundred mm or more. As a result, the spatial resolution of the interferometer of the object may drop due to the effect of the geometric unsharpness caused by the X-ray source having a finite size.

[0010] A drop in the spatial resolution due to the effect of geometric unsharpness can be suppressed by using a smaller sized X-ray source, but this decreases the X-ray generation amount per unit time, which in turn increases the imaging time. On the other hand, the high-speed imaging becomes possible by using a larger sized X-ray source, but this increases the effect of geometric unsharpness, and causes a drop in spatial resolution.

[0011] In the case of the method disclosed in Patent Literature 2, information on the interference pattern can be transferred based on the principle of the coded source imaging method, and it is theoretically possible to improve the spatial resolution of the imaging system when acquiring an object image, compared with the case of using a normal source grating.

However, normally the pixel size of the X-ray detector is larger than the interference pattern period, and the ratio of these sizes is often at the one-digit level. In concrete terms, the interference pattern period is normally several μm, but the pixel size is often several tens μm.

Therefore the inventors of the present invention discovered that in order to create an interference pattern, it is critical to sufficiently transfer the frequency components that correspond to a several μm period, and in order to significantly improve the sharpness of the finally detected image and the spatial resolution of the imaging system, it is critical to sufficiently transfer the frequency components that correspond to a several tens to several hundreds μm period, which normally is several times the pixel size.

[0012] Hence in order to significantly improve the spatial resolution for an object while transferring the interference pattern information when noise, including shot noise, is present, the MTF values corresponding to a several μm period and those corresponding to a several tens to several hundreds μm period must be simultaneously and sufficiently improved in the formation of periodic pattern images including information on the object. Through examination the inventor of the present invention discovered that a coded aperture mask having a general coded aperture pattern, such as a random array, is in many cases insufficient to implement such MTFs.

[0013] With the foregoing in view, it is an object of the invention to provide an X-ray imaging system which can perform imaging at higher resolution or at a higher speed than prior arts.

Citation List

Patent Literature

[0014]

PTL1: USP 5812629

PTL2: USP 7920673

Non-patent Literature

[0015]

NPL1: A. L. Damato, et al., "Coded Source Imaging for Neutrons and X-Rays", 2006 IEEE Nuclear Science Symposium Conference Record, 199-203

Summary of Invention

[0016] The present invention provides an X-ray imaging system, comprising: a source grating configured to convert each micro X-ray source of a micro X-ray source array into a plurality of even smaller X-ray sources; a beam splitter grating configured to diffract an X-ray having passed through the source grating and to form an interference pattern; an analyzer grating configured to have a pattern for forming moire with the interference pattern; and an X-ray detector configured to image the moire formed between the interference pattern and the pattern of the analyzer grating.

[0017] Further features of the present invention will become apparent from the following description of exemplary embodiments with reference to the attached drawings.

Brief Description of Drawings

[0018] Fig. 1A to Fig. 1C show examples of a coded source pattern;

Fig. 2 is a diagram depicting an example of MTF curves corresponding to the coded source patterns in Fig. 1A to Fig. 1C;

Fig. 3A and Fig. 3B are schematic diagrams depicting an X-ray imaging system according to Embodiment 1;

Fig. 4 are schematic diagrams depicting an X-ray imaging system according to Embodiment 2;

Fig. 5 is a schematic diagram depicting an example of a structure of an X-ray tube according to Embodiment 3;

Fig. 6A and Fig. 6B are examples of a coded aperture mask and a source grating according to Example 1;

Fig. 7A to Fig. 7F show examples of a moire image acquired by Example 1, and decoded results thereof;

Fig. 8A to Fig. 8C show examples of moire analysis results acquired by Example 1;

Fig. 9 is a diagram depicting an example of a source grating having a function of a coded aperture mask according to Example 2;

Fig. 10A to Fig. 10C show examples of moire images acquired by Example 4; and

Fig. 11A to Fig. 11F show examples of moire analysis results acquired by Example 4 and decoded results thereof.

Description of Embodiments

[0019] Preferred embodiments of the present invention will now be described with reference to the accompanying drawings. In each drawing, same composing elements are denoted with a same reference number, where redundant description is omitted.

[0020] An object of the present invention is to provide an X-ray imaging system based on the Talbot interferometry, that can have higher resolution and can perform higher speed imaging than prior arts by using the coded source imaging method.

However the inventors of this invention discovered that even if the source grating is replaced with the coded aperture mask, it is difficult to significantly improve the spatial resolution for an object while transferring the interference pattern information in a state where noise, including shot noise, exists. At least it is impossible to achieve this object of the invention by using a general coded source pattern, such as a random array. This will be explained first using a simple example.

[0021] Fig. 1A to Fig. 1C show typical random array type coded source patterns. Here it is assumed that a square grating is the basic structure, and circular micro

X-ray sources (white portions) are disposed on the grating points thereof at 1/2 probability. A diameter of the circular ray source is 1/2 that of the grating period. The overall sizes shown in Fig. 1A to Fig. 1C are the same, where patterns are formed such that 4 × 4, 8 × 8 and 16 × 16 grating points are included respectively.

[0022] PSF, which indicates the effect of geometric unsharpness, is a function that substantially has a form that is the same as the X-ray intensity distribution, which is formed when an X-ray is irradiated with disposing a single pinhole of which diameter is sufficiently small (but large enough not to cause the obvious influence of diffraction) at a position where the object is disposed. As a result, the form of PSF is substantially the same as the form of the coded source. Therefore here it is approximated that PSF, which indicates the effect of geometric unsharpness, generated by each coded source pattern shown in Fig. 1A to Fig. 1C, has a pattern that is the same as the respective coded source pattern.

[0023] Generally in the coded source imaging method, the spatial resolution is determined by the diameter of the micro source. This is because the spatial frequency at which the MTF value virtually becomes zero (hereafter called "cut-off frequency") is determined largely by the diameter of a bright portion in the PSF image corresponding to an individual micro source. If this is the case, then the highest cut-off frequency is expected in the pattern shown in Fig. 1C, in the comparison between the patterns in Fig. 1A to Fig. 1C.

[0024] Fig. 2 shows a part of the MTF curves corresponding to each pattern in Fig. 1A to Fig. 1C, where the patterns are regarded as PSF. Here D′ denotes a width of the entire PSF (approximate width of the square where dots are distributed), and an MTF value on one line that passes through the origin of the frequency coordinate is shown. The high peaks at the positions of spatial frequencies 4/D′, 8/D′ and 16/D′ in each curve are peaks corresponding to the basic spatial frequency of the square grating, which is the basic structure of each PSF.

[0025] As mentioned above, of the patterns in Fig. 1A to Fig. 1C, the highest cut-off frequency is expected in the pattern shown in Fig. 1C (16 × 16), and this can also be recognized to some extent in the comparison of the MTF curves in Fig. 2. Therefore if the SN (signal-to-noise) ratio of the detected image data is sufficiently high, the highest spatial resolution is expected in the pattern described in Fig. 1C, among the patterns in Fig. 1A to Fig. 1C.

[0026] However, if the SN ratio of the detected image data is not sufficiently high, a sufficient SN ratio cannot be acquired unless the frequency region has a high signal amount and high MTF value. In such a case, the spatial resolution is not determined by the cut-off frequency alone based on the above mentioned definition, and the MTF value in the low frequency region also has critical significance.

[0027] By again comparing each MTF curve in Fig. 2, it is observed that the MTF value in the low frequency region of the pattern in Fig. 1C (16 × 16), of which cut-off frequency is highest, is much lower than the MTF value of the pattern in Fig. 1A (4 × 4).

[0028] As assumed in this comparison, as the individual micro source becomes smaller in the coded source pattern, and a number of micro sources is increased at the same time to compensate for the decreased size, the cut-off frequency increases, but the MTF value in the low frequency region tends to drop. Therefore the pattern in Fig. 1C, for example, has a potential to implement a higher spatial resolution than the pattern in Fig. 1A, but it is rather difficult to significantly improve the spatial resolution under the state where a certain level of noise exists.

[0029] In other words, a rough pattern, as shown in Fig. 1A, is required to dramatically improve the MTF value in a relatively low frequency region, but such a rough pattern cannot dramatically improve the MTF value in the high frequency region. On the other hand, a micro-pattern such as in Fig. 1C is required to dramatically improve the MTF value in the high frequency region, however such a micro-pattern cannot dramatically improve the MTF value in the low frequency region. In this way, it is generally difficult to dramatically increase the MTF value throughout a wide range of frequency regions using a conventional coded source pattern, such as a random array.

[0030] Therefore as mentioned above, it is normally difficult to simultaneously implement both a transfer of interference pattern information having a fine period and an improvement in the spatial resolution for an object, since the spatial frequency region that is critical for the period of the interference pattern and the pixel size has about a one-digit difference.

[0031] The Talbot interferometer according to the embodiment of the present invention includes both the coded X-ray source and the source grating. The source grating has a configuration where the micro X-ray transmitting portions are arrayed one-dimensionally or two-dimensionally at a predetermined period, in order to generate an interference pattern by the Talbot effect. By using this source grating, the interference pattern information having a fine period can be transferred. The coded X-ray source, on the other hand, has a configuration where the size of a plurality of micro X-ray sources and the arrangement thereof are designed so that PSF (MTF) thereof has a predetermined form (including various spatial frequency components), in order to improve the spatial resolution in the imaging system. Typically the size and the period of each X-ray transmitting portion of the source grating should be sufficiently smaller than the size of each micro X-ray source of the coded- X-ray source. In other words, each micro X-ray source of the coded X-ray source should be further divided into a plurality of ultramicro X-ray sources by the source grating. In concrete terms, the period of the source grating is preferably 1/5 or less of the size of the micro X-ray sources of the coded X-ray source, and more preferably 1/10 or less.

[0032] Fig. 3A is a schematic diagram depicting a configuration of a Talbot interferometer according to an embodiment of the present invention. This interferometer includes a coded X-ray source 1, a source grating 2, a beam splitter grating 3, an analyzer grating 4, an X-ray detector 5, an image processing device 6, and a beam splitter grating moving unit 7. The coded X-ray source is an array of micro X-ray sources, and the source grating 2 is a grating for converting the coded X-ray source 1 into a plurality of even smaller X-ray sources. The beam splitter grating 3 is a grating for forming an interference pattern by diffracting the X-ray that has passed through the source grating 2 (and an object), and the analyzer grating 4 is a grating having a pattern to generate moire with the interference pattern. The source grating is a grating in which the X-ray transmitting portions and X-ray shielding portions are arranged. The X-ray transmitting portions are arranged so that each bright portion and dark portion of the interference pattern, which is formed by an X-ray that is transmitted through a certain X-ray transmitting portion and is diffracted by the beam splitter grating, are superimposed on each of the bright portions and dark portions of the interference pattern, which is formed by an X-ray that is transmitted through another X-ray transmitting portion and is diffracted by the beam splitter grating. The beam splitter grating is a diffraction grating, and can be either a phase type diffraction grating (phase grating) that periodically modulates the phase of the X-ray, or an amplitude type diffraction grating (shield grating) that periodically modulates the amplitude of the X-ray, but the phase grating is more frequency used since the loss of X-rays is small. For the analyzer grating, the X-ray shield grating, where the X-ray transmitting portions and the X-ray shielding portions are arrayed is often used. The X-ray detector can be any detector that can detect an X-ray, but an X-ray detector that can acquire two-dimensional intensity distribution is preferable to widen the imaging range. The image processing device is a computer that has a processor, a memory, a storage device, an input/output device or the like, or a logic circuit, and may use both the computer and the logic circuit.

The shapes of these three gratings, the configurations of the X-ray detector and the image processing device, and the arrangement thereof can be designed according to a well-known design method for a

Talbot-Lau interferometer. Each grating may have a one-dimensional periodic structure or a two-dimensional periodic structure. 8 indicates an object.

[0033] According to this configuration, the source grating 2 has a function to form a fine interference pattern, therefore the pattern of the coded X-ray source 1 can be freely selected independently from the function to form the interference pattern.

[0034] As the description thus far clarifies, it is not preferable to increase a number of micro X-ray sources of the coded X-ray source by decreasing the diameter of each micro X-ray source to less than the diameter required to improve spatial resolution, because it becomes difficult to improve MTF in a low frequency region.

[0035] A diameter d_L in a local maximum portion (lobe) in PSF, for forming an object image on the detector 5, is given by $d_L = (L_2/L_1) \times d_S$, where d_S denotes a diameter of the micro X-ray source, L_1 denotes a distance between the coded X-ray source 1 and the object 8, and L_2 denotes a distance between the object 8 and the X-ray detector 5. When an image is detected by the detector 5, a frequency exceeding the Nyquist frequency, of which period corresponds to double the pixel size (pixel pitch), cannot be detected normally, hence decreasing d_L to be less than the pixel size, for example, contributes little to the improvement of spatial resolution. Therefore when the pixel size of the detector 5 is d_P, it is preferable that

$d_L > d_P$ is established. In other words, it is preferable that

$$d_S > (L_1/L_2) \times d_P \quad \text{(Expression 1)}$$

is established.

[0036] This configuration can suppress a drop in spatial resolution due to the effect of geometric unsharpness, therefore an imaging system with higher magnification than usual can be more easily used. The magnification here is normally determined by $(L_1 + L_2)/L_1$, but to improve magnification, $L_1 < L_2$, for example, may be used to design the Talbot interferometer.

[0037] In the Talbot interferometer, it is preferable, in terms of sensitivity to differential phase measurement, that the distance from the source grating 2 to the analyzer grating 4 is long, and that the beam splitter 3 is close to the object.

Therefore in the present invention, a Talbot-Lau interferometer having a standard design can be used, but for a high magnification system with $L_1 < L_2$, it is preferable to design such that the distance from the source grating 2 to the beam splitter grating 3 is shorter than the distance from the beam splitter grating 3 to the analyzer grating 4. This design is called "inverse geometry". An advantage of this imaging system is that high spatial resolution can be easily acquired, and that the analyzer grating 4, for which a largest area is demanded, can be more easily fabricated since the period of the analyzer grating 4 becomes relatively large. Fig. 3A was drawn assuming that a Talbot-Lau interferometer has an inverse geometry.

[0038] In Embodiment 1, a case of forming a coded X-ray source 1 using a coded aperture mask will be described. In Embodiment 2, a case of integrating the coded aperture mask and the source grating 2 will be described. In Embodiment 3, a case of configuring the coded X-ray source 1 using an X-ray tube having a special structure will be described. In Embodiment 4, a case of using a decoding method, which is different from the usual case, will be described.

[0039] [Embodiment 1]

In this embodiment, the coded X-ray source 1 is formed using a coded aperture mask. For example, the coded X-ray source 1 is configured by an X-ray tube and a coded aperture mask disposed very close to an X-ray generating part of the X-ray tube. The coded aperture mask partially shields the X-rays emitted from the X-ray generating part of the X-ray tube, whereby an array of micro X-ray sources, having a desired pattern, is formed virtually. The coded aperture mask is a mask having an X-ray shielding portion, where a plurality of apertures are opened. It is preferable that each of the apertures is a pinhole. In this way the coded X-ray source can be a virtual array of micro X-ray sources.

[0040] In this embodiment, a diameter d_S of each micro

X-ray source in the coded X-ray source 1 matches with a diameter d_H of each aperture of the coded aperture mask. Therefore in order to effectively utilize the effect of the coded source imaging method by the imaging system satisfying Expression (1), it is preferable to satisfy $d_H > (L_1/L_2) \times d_P$.

[0041] In the case of a Talbot interferometer, a moire, which is generated between an interference pattern formed by the beam splitter grating 3 and a pattern of the analyzer grating 4, is imaged by an X-ray detector 5. In this embodiment, a moire image, coded by the coded X-ray source 1, is acquired. This moire image reflects information indicating the X-ray intensity distribution. The coded-moire image acquired by the X-ray detector 5 is converted into a moire image that is closer to that imaged by a single micro X-ray source, by the decoding processing of an image processing device 6. However the image forming process by the Talbot interferometer is more complicated than a normal X-ray imaging, hence a correct image may not be restored by a simple deconvolution processing. For example, if the period of a moire pattern is as small as the scale of the geometric unsharpness, an accurate restoration of the image sometimes becomes difficult. This problem can occur less if the "period of moire when no object exists" is three times or more than the "width of an area where PSF has a significant value". The "range of an area where PSF has a significant value" is given by $(L_2/L_1) \times D$, where D denotes an effective diameter of the entire coded X-ray source 1. Therefore if the "period of moire when no object exists" is d_M, it is preferable to satisfy $d_M > 3 \times (L_2/L_1) \times D$.

[0042] The decoding processing is performed by the image processing device 6. In concrete terms, the moire image can be decoded by deconvolution calculation based on information on estimated values or measured values of PSF, for example.

[0043] Further, the image processing device 6 may perform analysis processing, such as phase retrieval, based on the decoded moire image that is acquired. It is preferable in this embodiment that the period of moire is larger than a predetermined value, as mentioned above, therefore an analysis method, where spatial resolution does not drop due to the influence of the moire period, is preferable. An example of such a method is a phase shift method. To use the phase shift method, it is necessary to acquire a plurality of moire images having different moire phases. In this embodiment, the moire phase can be shifted by moving the beam splitter grating in the in-plane direction using a moving unit 7 that moves the beam splitter grating. An actuator can be used for the moving unit that moves the beam splitter grating. The moving unit may move the source grating or the analyzer grating, instead of the beam splitter grating, to move the interference pattern, since the phase of the moire shifts if the relative positions between the interference pattern and the analyzer grating are changed. Details on the algorithms of the phase shift method are stated in many books on interferometers, such as Daniel Malacara, ed., Optical Shop Testing, Third Edition, Chapter 14, therefore details are omitted here. By the analysis of the moire image, primarily three images are acquired: an X-ray absorptivity distribution of the the object 8; a differential phase distribution of the X-ray transmitted through the object 8; and an X-ray small-angle scattering power distribution of the object 8 (visibility distribution of the moire pattern).

[0044] [Embodiment 2]

In a Talbot interferometer according to an X-ray imaging system of Embodiment 2, a coded X-ray source is configured by a source grating integrated with a coded aperture mask. In other words, the source grating has not only its original functions, but also the functions of the coded aperture mask according to Embodiment 1.

[0045] Fig. 4 is a schematic diagram depicting a configuration of a Talbot interferometer according to this embodiment. In this embodiment, the X-ray source 9 functions as the coded X-ray source due to the presence of the source grating 2. This source grating 2 may be configured by bringing the coded aperture mask and the source grating into close contact with each other, for example, or may be configured by one X-ray shielding mask which has a transmittance distribution equivalent to the close contact of the coded aperture mask and the source grating. In this embodiment, the source grating 2 must be disposed very close to the X-ray source 9, unlike the standard Talbot-Lau interferometer.

[0046] The source grating 2 having the functions of the coded aperture mask according to this embodiment can also be regarded as a kind of coded aperture mask having the functions of the source grating. For example, as the MTF curve in Fig. 2 shows, in some cases the MTF curve may have a high peak at a spatial frequency corresponding to the period of this basic structure of the PSF pattern which reflects the pattern of the coded source. This means that the interference pattern can easily be formed by matching the period of the basic structure and the period of the interference pattern. Forming an interference pattern using a conspicuous peak in the MTF curve like this is equivalent to providing the functions of the source grating to the coded-aperture pattern.

[0047] As mentioned above, even if this method is used, improving MTF in the low frequency region is difficult in the coded source pattern, such as a random array. However if it is regarded that the coded source pattern is formed by superposing of the source grating pattern and the coded source pattern, which is rougher than the source grating pattern, and the coded source pattern alone is rough enough to satisfy Expression (1), for example, then it is more possible to implement the effect of improving MTF in the low frequency region as well. When it is regarded that the coded source pattern is formed by superposing the source grating pattern and the coded source pattern, which is rougher than the source grating pattern, if the PSF of this coded source pattern is Fourier-transformed, then a peak occurs at a position that matches with the spatial frequency of the interference pattern.

The acquisition of a moire image, decoding processing, analysis processing or the like can be performed in the same manner as Embodiment 1.

[0048] [Embodiment 3]

In Embodiment 3, the coded X-ray source 1 is formed by an X-ray tube having a special structure. Fig. 5 is an example of the X-ray tube structure according to this embodiment. In Fig. 5, it is assumed that a rotating anode type X-ray tube is used, where 101 denotes a rotating anode (target), 102 denotes a rotation axis of the target 101, 103 denotes an electron beam incident on the target, and 104 denotes an X-ray that is emitted from the target. Fig. 5 is a cross-sectional view of the target 101, and the target 101 has a rotationally symmetric shape with respect to the rotation axis 102. The electron beam 103 is distributed to be sufficiently thin in a direction that is perpendicular to the paper surface.

[0049] The target 101 shown in Fig. 5 has a plurality of grooves formed in an electron beam incident portion. As mentioned above, the target 101 has a rotationally symmetric shape with respect to the rotation axis 102, hence these grooves are formed concentrically around the rotation axis 105 of the target. As shown in Fig. 5, an X-ray is not emitted from the groove portions of the target surface, only the portions between the grooves (the apex of each wall (ridge) between grooves) contribute to the emission of an X-ray. Thereby the surface (electron beam incident surface) of the target is finely divided into a plurality of X-ray emission surfaces, and a coded X-ray source 1 having a one-dimensional pattern is formed. The plurality of X-ray emission surfaces are separated in the radial direction of the rotation axis 102.

[0050] Here it is assumed that the diameter (or the width) d_T of the X-ray emission surface is a dimension of the area shown in Fig. 5, and an angle formed by the X-ray emission surface and the center line of the X-ray beam that is emitted from the X-ray emission surface to the X-ray detector (object) (that is, the X-ray emission angle), is θ. Then the diameter d_S of an effective micro X-ray source formed by an individual X-ray emission surface roughly matches with $d_T \times \sin\theta$. Therefore in order to use the effect of the coded source imaging method by the imaging system satisfying Expression (1), it is preferable to satisfy $d_T \times \sin\theta > (L_1/L_2) \times d_P$. Here L_1 denotes a distance between the X-ray emission surface of the target

101 and the object. L_2 denotes a distance between the object and the X-ray detector, and d_P denotes the pixel size of the X-ray detector.

[0051] The diameter d_T of the X-ray emission surface and the interval from the center of a groove to the center of the next groove need not be uniform. Beside the method of forming an unevenness on the electron beam incident surface of the target, as shown in Fig. 5, a plurality of X-ray emission surfaces may be formed by combining a plurality of target materials having different X-ray generation efficiencies for the electron beam incident surfaces. A plurality of X-ray emission surfaces can also be formed by a configuration that allows a plurality of spatially separated electron beams incident on the target. Further, the rotation of the target is not essential, and a stationary type target may be used.

The arrangement of the gratings, detection of a moire image, decoding processing, analysis processing or the like can be performed in the same manner as Embodiment 1.

[0052] [Embodiment 4]

The methods of decoding a detected moire image were described in Embodiments 1 to 3. However as mentioned above, the image forming process in the Talbot interferometer is more complicated than normal X-ray imaging, and particularly when the moire period is small, the accuracy of decoding is sometimes affected.

[0053] To handle this problem, the moire image itself is not decoded in this embodiment. In other words, the image processing device 6 performs analysis processing based on a moire image acquired in a coded state first, and then performs decoding processing for the acquired X-ray absorptivity distribution, transmitted X-ray differential phase distribution, X-ray small-angle scattering power distribution, or the like of object 8, using such a method as deconvolution.

[0054] In this embodiment, the accuracy of the decoding may be decreased compared with the case of decoding a moire image as in Embodiments 1 to 3, but an advantage is that decoding processing is performed with a consistent performance regardless the period of moire.

The image processing method of this embodiment can also be applied to a Talbot interferometer having any one of the configurations described in Embodiment 1 to 3.

[0055] This embodiment is also suitable for performing the moire image analysis by the Fourier transform method, since the period of moire can be shortened. Details on the Fourier transform method is reported on in Mitsuo Takeda et al, "Fourier transform method of fringe pattern analysis for computer-based topography and interferometry", Journal of the Optical Society of America, Vol. 72, No. 1, pp. 156-160 (1982), therefore description thereof is omitted here. To perform the Fourier transform method, the period of moire is often set to several times the pixel size, therefore if the period of moire is at this level, it is preferable to perform the decoding processing after the moire analysis processing in this embodiment.

[0056] Concrete examples of each embodiment will now be described.

[0057] (Example 1)

Example 1 is a concrete example of Embodiment 1. Fig. 3A is a schematic diagram depicting a general configuration of an X-ray imaging system of Example 1, and Fig. 3B is a schematic diagram depicting a configuration of a coded X-ray source 1 according to Example 1.

[0058] The coded X-ray source 1 is configured by an X-ray tube 111 and a coded aperture mask 112, which is installed very close to the X-ray emitting portion of the X-ray tube 111. The X-ray tube 111 is an X-ray tube having a molybdenum target, and emits an X-ray having an energy spectrum where the characteristic X-ray peak is at the position of 17.5 keV.

[0059] Fig. 6A is a pattern of a coded aperture mask 112. A diameter d_H of an individual aperture (pinhole) in Fig. 6A is 120 μm. The X-ray shielding portion is 50 μm thick gold. The effective diameter D of the entire X-ray emitting portion of the coded X-ray source 1, which corresponds to the diameter of the entire area where the pinholes are distributed on the coded aperture mask 112, is approximately 600 μm.

[0060] In this example, imaging is performed with adjusting the position and the angle of each grating, so that the moire period d_M when no object exists becomes substantially infinite. Therefore the above mentioned $d_M > 3 \times (L_2/L_1) \times D$ is satisfied, and an accurate decoding of the moire image can be expected.

[0061] Fig. 6B shows a pattern of the source grating 2. The source grating 2 has a structure where the linear X-ray transmitting portions are disposed on the X-ray shielding mask at equal intervals. The interval from the center of an X-ray transmitting portion to the center of the next X-ray transmitting portion is 10.3 μm, and the width of the X-ray transmitting portion is 5.15 μm. The X-ray shielding portion is 50 μm thick gold, and the X-ray transmitting portion is an aperture.

[0062] The beam splitter grating 3 is a phase modulation type diffraction grating, and has a structure where a linear phase advancing portion and a linear phase delaying portion are alternately disposed. The width of the phase advancing portion and the width of the phase delaying portion are both 6.87 μm. The material of the grating is silicon. Since the thickness of the phase advancing portion is 22.3 μm thicker than the thickness of the phase delaying portion, the π rad of the phase difference can be provided to the X-ray with 17.5 keV when the X-ray is transmitted through this grating.

[0063] Just like the source grating 2, the analyzer grating 4 has a structure where the linear X-ray transmitting potions are disposed on the X-ray shielding mask at equal intervals. The interval from the center of an X-ray transmitting portion to the center of the next X-ray transmitting portion is 20.6 μm, and the width of the X-ray transmitting portion is 10.3 μm. The X-ray shielding portion is 50 μm thick gold, and the X-ray transmitting portion is an aperture.

[0064] The source grating 2 is disposed near the coded X-ray source 1. The distance between the source grating 2 and the beam splitter grating 3, and the distance between the beam splitter grating 3 and the analyzer grating 4 are adjusted to 500 mm and 998 mm respectively. The object 8 is disposed very close to the beam splitter grating 3, and the X-ray detector 5 is disposed very closely to the analyzer grating 4. The pixel size d_P of the X-ray detector 5 is 50 μm.

[0065] If the above mentioned design values are used, this imaging system satisfies $d_H > (L_1/L_2) \times d_P$, therefore the effect of the coded source imaging method can be expected to be effectively utilized.

[0066] This example will now be described using the image data of a moire image, which is assumed to be detected by this imaging system, and the result of decoding and moire analysis using this image data.

[0067] Fig. 7A to Fig. 7C show coded moire images which are detected by shifting the phase of the moire by $2\pi/3$ rad. Here two spherical objects were used as the object

8. It is also assumed that the moire period when no object exists becomes substantially infinite, as mentioned above. Furthermore, the presence of shot noise at a certain scale is assumed.

[0068] Fig. 7D to Fig. 7F are the results of decoding each moire image in Fig. 7A to Fig. 7C using the image processing device 6. As a result of the decoding processing, images close to the moire images captured by a single micro X-ray source are acquired.

[0069] Fig. 8A to Fig. 8C are the result of analyzing Fig. 7D to Fig. 7F based on algorithms of the phase shift method. Fig. 8A to Fig. 8C show the X-ray transmittance distribution, the X-ray differential phase distribution and the X-ray small-angle scattering power distribution respectively. As Fig. 8A to Fig. 8C show, the analysis result, which is close to each analysis result acquired by a single micro X-ray source, can be acquired at relatively high spatial resolution.

[0070] (Example 2)

Example 2 is a concrete example of Embodiment 2. In this example, the coded X-ray source is configured by a source grating 2 having functions of the coded aperture mask. Fig. 9 shows a pattern of the source grating 2 according to this example. Here it is assumed that the pattern is substantially equivalent to a pattern when the coded aperture mask and the source grating 2 in Example 1 are brought into close contact with each other. In other words, the diameter of the circular slit distribution area in Fig. 9 is 120 μm, the interval from the center of the slit to the center of the next slit is 10.3 μm, and the width of the slit is 5.15 μm. The X-ray shielding portion is 50 μm thick gold, and the X-ray transmitting portion is an aperture. In this example, it is preferable that the source grating 2 is disposed very close to the X-ray emission portion of the X-ray tube.

[0071] The rest of the details and the arrangement of the X-ray tube, each grating, the X-ray detector or the like are the same as Example 1. By using the source grating 2 having the functions of the coded aperture mask like this, moire images can be detected, decoded and analyzed in the same way as Example 1.

[0072] (Example 3)

Example 3 is a concrete example of Embodiment 3. In this example, the coded X-ray source 1 is configured using the X-ray tube that has a structure similar to that shown in Fig. 5. Thereby a coded X-ray source having a pattern, in which micro X-ray sources are one-dimensionally disposed, can be acquired.

[0073] The material of the rotating target 101 in this example is molybdenum, and grooves are formed concentrically at equal intervals on the target 101. The width of a groove is 240 μm, the depth thereof is 200 μm, and the interval from the center of a groove to the center of the next groove is 480 μm. In other words, the diameter d_T of the X-ray emission surface is 240 μm. The X-ray emission angle θ is 30°. Therefore the effective coded X-ray source 1 has a pattern in which micro X-ray sources having about a 120 μm diameter are one-dimensionally disposed at a 240 μm period.

The rest of the details and the arrangement of each grating, the X-ray detector or the like are the same as Example 1.

[0074] If the above mentioned design values are used, this imaging system satisfies $d_T \times \sin\theta > (L_1/L_2) \times d_P$, therefore the effect of the coded source imaging method can be expected to be effectively utilized.

By configuring the coded X-ray source 1 by the X-ray tube having a special structure like this, moire images can be detected, decoded and analyzed in the same way as Example 1.

[0075] (Example 4)

Example 4 is a concrete example of Embodiment 4. Except for the decoding and analysis processings by the image processing device 6, Embodiment 4 is the same as the other embodiments, therefore the configuration of Example 4 other than the configuration of the image processing device 6 is the same as Example 1. Here a case of the moire period d_M, when no object exists, that is smaller by a certain degree due to the relative in-plane rotation of the gratings, will be described as an example.

[0076] Fig. 10A to Fig. 10C show coded moire images which are detected by shifting the phase of the moire by $2\pi/3$ rad. Here just like Example 1, two spherical objects were used as the object 8. Furthermore, the presence of shot noise at a certain scale is assumed.

[0077] Fig. 11A to Fig. 11C are results of performing analysis on Fig. 10A to Fig. 10C based on algorithms of the phase shift method. Fig. 11A to Fig. 11C show the X-ray transmittance distribution, the X-ray differential phase distribution and the X-ray small-angle scattering power distribution. As Fig. 11A to Fig. 11C show, these results are similar to the images generated when each analysis result acquired by imaging using a single micro X-ray source is convoluted by PSF in which the coded source pattern is reflected.

[0078] Fig. 11D to Fig. 11F show the result when the temporary analysis result in Fig. 11A to Fig. 11C is decoded by the image processing device 6. Fig. 11D to Fig. 11F show that an appropriate analysis result can be acquired at a relatively high spatial resolution.

By performing decoding processing, not directly on the moire image, but on the temporary analysis result of the moire, the coded source imaging method can be effectively used even if the moire period is short.

[0079] Preferred embodiments of the present invention have been described, but the present invention is not limited to these embodiments, but can be modified and changed in various ways within the scope of the true spirit of the invention. In the present invention and in the present description, the "imaging" is not limited to acquiring an image based on the information of an object, but refers to detecting the intensity of an X-ray irradiated onto the object at a plurality of locations.

[0080] According to the present invention, an X-ray imaging system, which can perform imaging at a higher resolution or at a higher speed than prior art, can be provided.

[0081] While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

This application claims the benefit of Japanese Patent Application No. 2013-188230, filed on September 11, 2013, and Japanese Patent Application No. 2014-178798, filed on September 3, 2014, which are hereby incorporated by reference herein in their entirety.

Reference Signs List

[0082]

1 coded X-ray source

2 source grating

3 beam splitter grating

4 analyzer grating

5 X-ray detector

6 image processing device

CLAIMS

1. An X-ray imaging system, comprising:

a source grating configured to convert each micro X-ray source of a micro X-ray source array into a plurality of even smaller X-ray sources;

a beam splitter grating configured to diffract an X-ray having passed through the source grating and to form an interference pattern;

an analyzer grating configured to have a pattern for forming moire with the interference pattern; and

an X-ray detector configured to image the moire formed between the interference pattern and the pattern of the analyzer grating.

2. The X-ray imaging system according to Claim 1, wherein

the micro X-ray source array includes an X-ray source, and a coded aperture mask configured to partially shield the X-ray emitted from the X-ray source.

3. The X-ray imaging system according to Claim 2, wherein

the coded aperture mask is an X-ray shielding mask where a plurality of apertures are formed corresponding to the plurality of micro X-ray sources respectively.

4. The X-ray imaging system according to Claim 3, wherein

a diameter d_H of each of the apertures formed in the coded aperture mask satisfies $d_H > (L_1/L_2) \times d_P$, where L_1 denotes a distance between the X-ray source and an object, L_2 denotes a distance between the object and the X-ray detector, and d_P denotes a pixel size of the X-ray detector.

5. The X-ray imaging system according to any one of Claims 2 to 4, wherein

the source grating and the coded aperture mask are integrated.

6. The X-ray imaging system according to Claim 2, wherein

the micro X-ray source array includes an electron beam source, and a target that emits an X-ray by allowing an electron beam to enter from the electron beam source, and the target has a plurality of X-ray emission surfaces.

7. The X-ray imaging system according to Claim 6, wherein

the target rotates around a rotation axis, and

the plurality of X-ray emission surfaces are formed separate from each other in a radial direction of the rotation axis.

8. the X-ray imaging system according to Claim 6 or 7, wherein

the plurality of X-ray emission surfaces are formed by creating unevenness on an electron beam incident surface of the target.

9. The X-ray imaging system according to Claim 6 or 7, wherein

the plurality of X-ray emission surfaces are formed by constituting an electron beam incident surface of the target with a combination of a plurality of materials having different X-ray generation efficiencies.

10. The X-ray imaging system according to Claim 6 or 7, wherein

the electron beam source allows a plurality of spatially separate electron beams to enter an electron beam incident surface of the target, such that the plurality of X-ray emission surfaces are formed.

11. The X-ray imaging system according to any one of Claims 6 to 10, wherein

a diameter d_T of at least one X-ray emission surface, out of the plurality of X-ray emission surfaces, satisfies $d_T \times \sin\theta > (L_1/L_2) \times d_P$, where θ denotes an angle formed by an X-ray emission surface and a center line of an X-ray beam that is emitted from the X-ray emission surface to the X-ray detector, L_1 denotes a distance between the X-ray emission surface and an object, L_2 denotes a distance between the object and the X-ray detector, and d_P denotes a pixel size of the X-ray detector.

12. The X-ray imaging system according to any one of Claims 1 to 11, wherein

a distance between the source grating and the beam splitter grating is shorter than a distance between the beam splitter grating and the analyzer grating.

13. The X-ray imaging system according to any one of Claims 1 to 12, wherein

a period d_M of the moire, which is formed when no object exists, satisfies $d_M > 3 \times (L_2/L_1) \times D$, where L_1 denotes a distance between the X-ray source and an object, L_2 denotes a distance between the object and the X-ray detector, and D denotes an effective diameter of an entire X-ray emission portion in the X-ray source.

14. The X-ray imaging system according to any one of Claims 1 to 13, further comprising an image processing device configured to perform decoding processing on a moire image acquired by the X-ray detector.

15. The X-ray imaging system according to any one of

Claims 1 to 13, further comprising an image processing device configured to perform decoding processing on at least one distribution out of a absorptivity distribution of the X-ray on an object, a differential phase distribution of the X-ray transmitted through the object, and a visibility distribution of moire, which are obtained by analyzing a moire image acquired by the X-ray detector.

FIG.1A

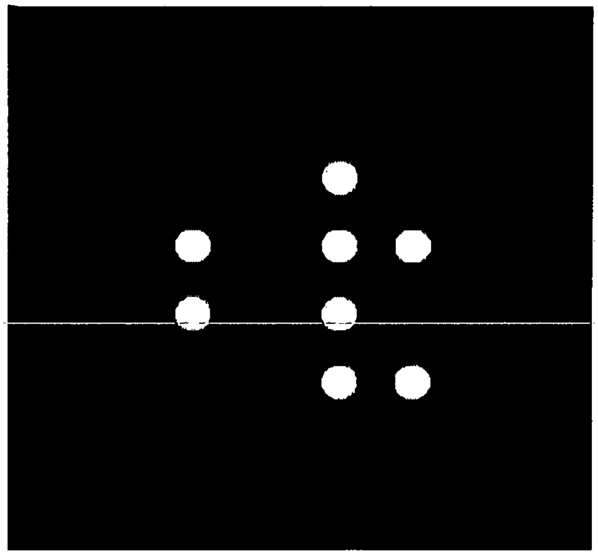


FIG.1B

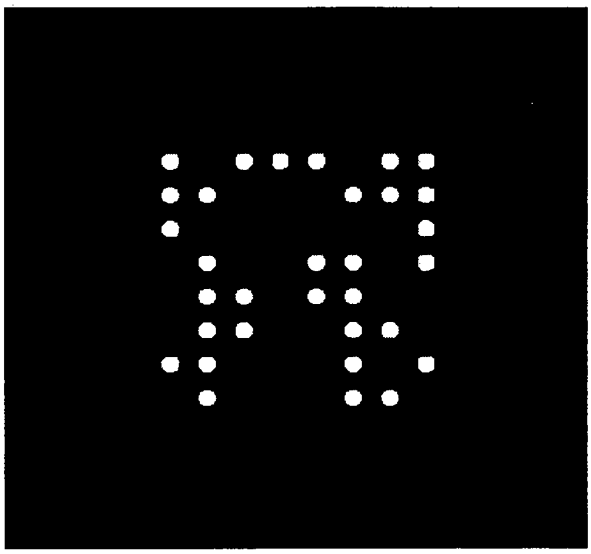


FIG.1C

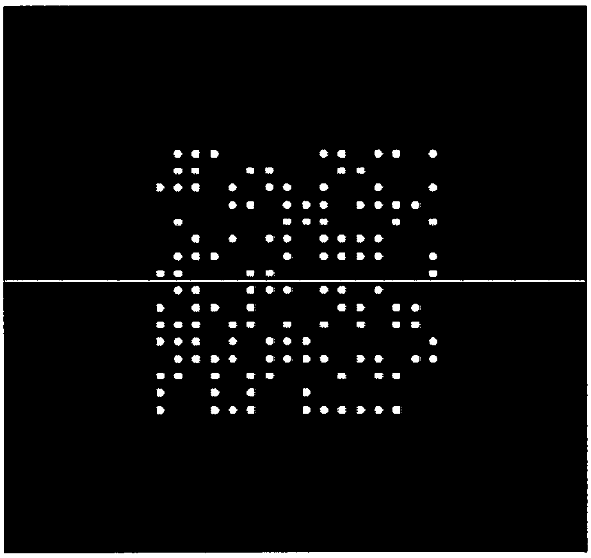
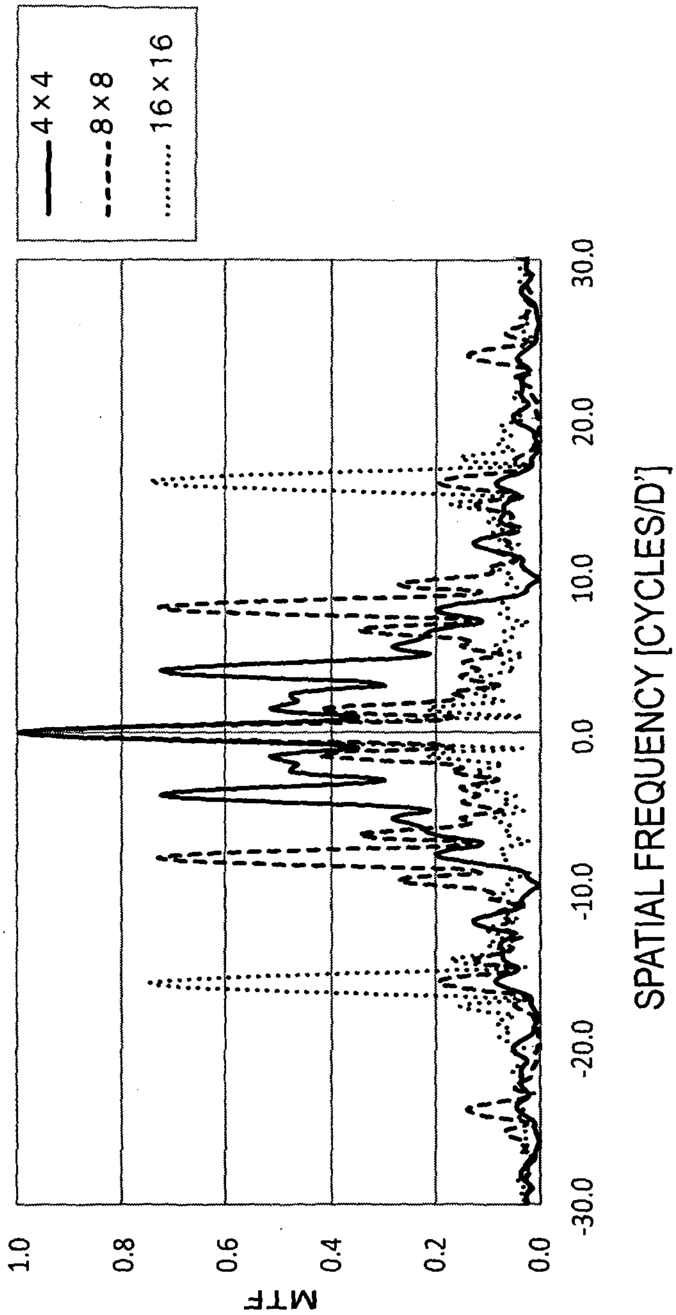


FIG.2


4×4
8×8
16×16
MTF
1.0
0.8
0.6
0.4
0.2
0.0
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0.0
10.0
20.0
30.0
SPATIAL FREQUENCY [CYCLES/D']

FIG.3A

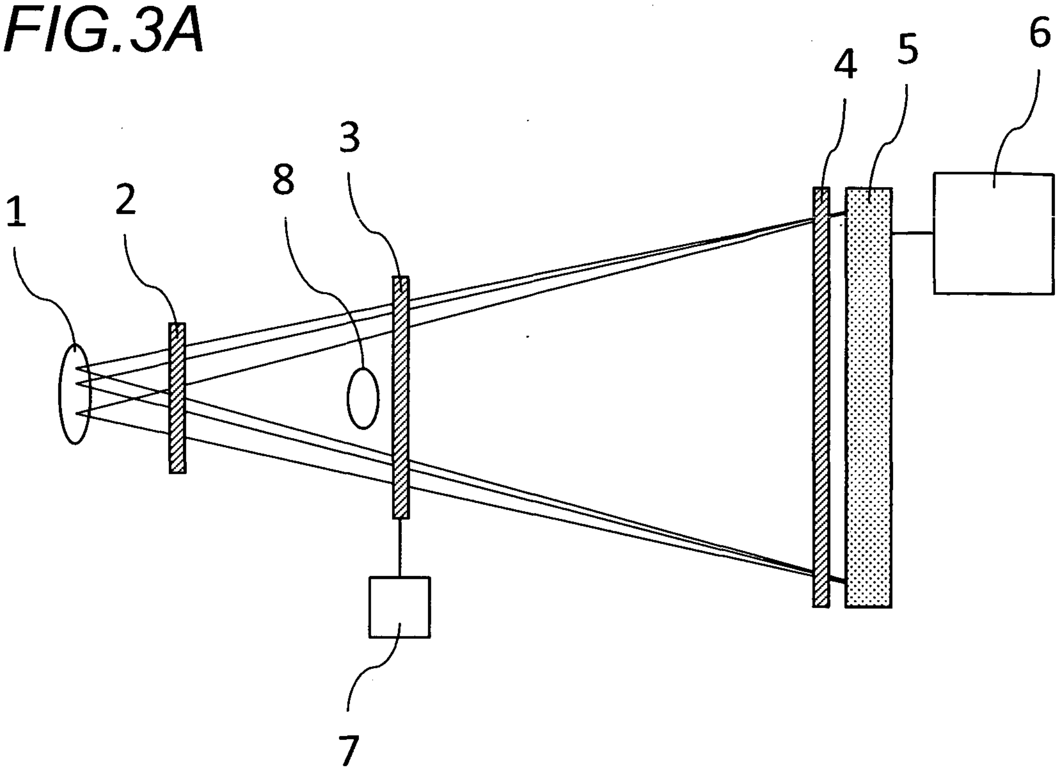


FIG.3B

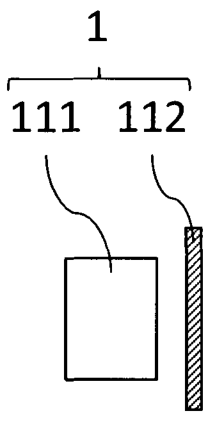


FIG.4

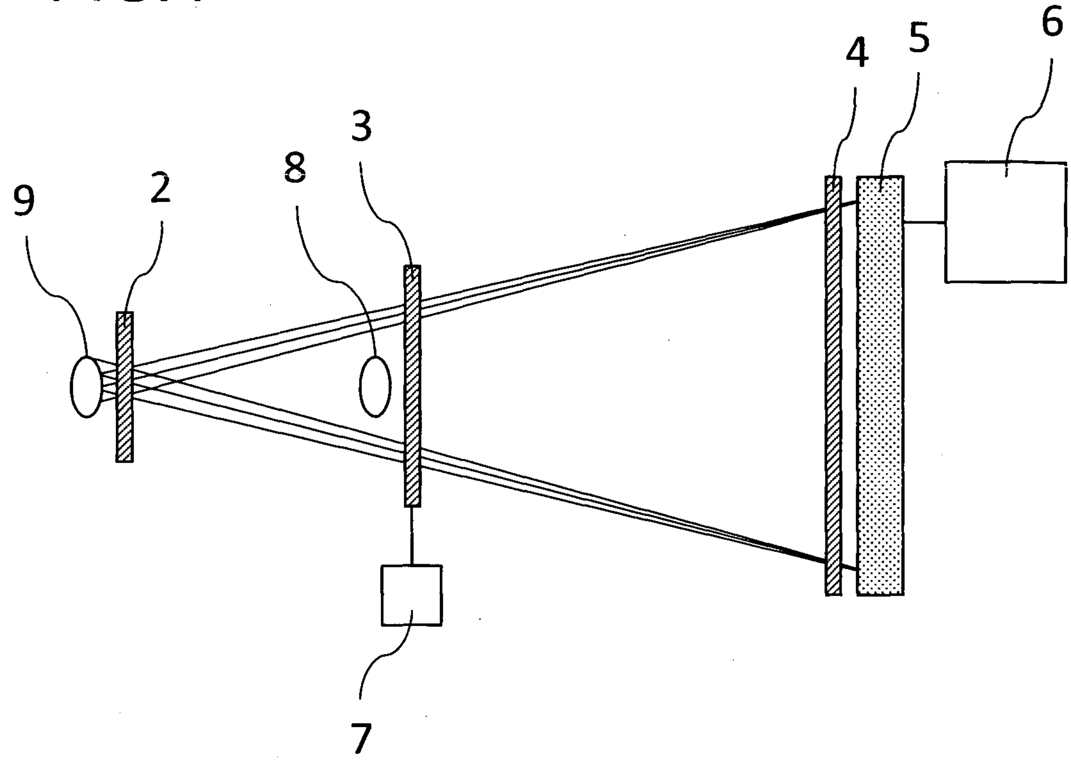


FIG.5

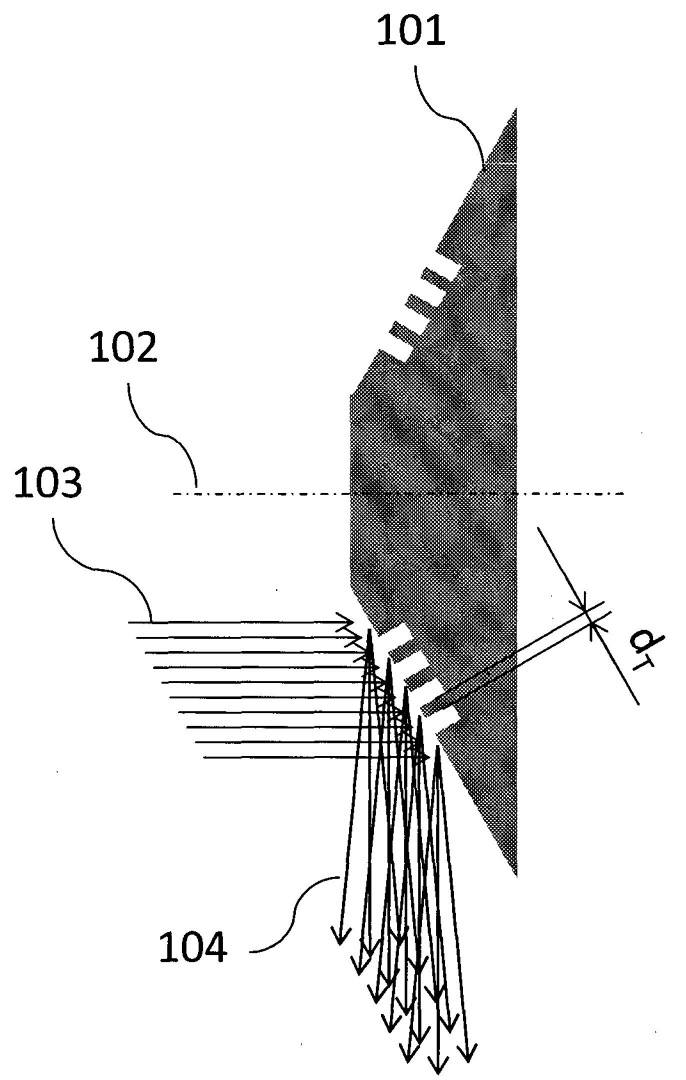


FIG.6A

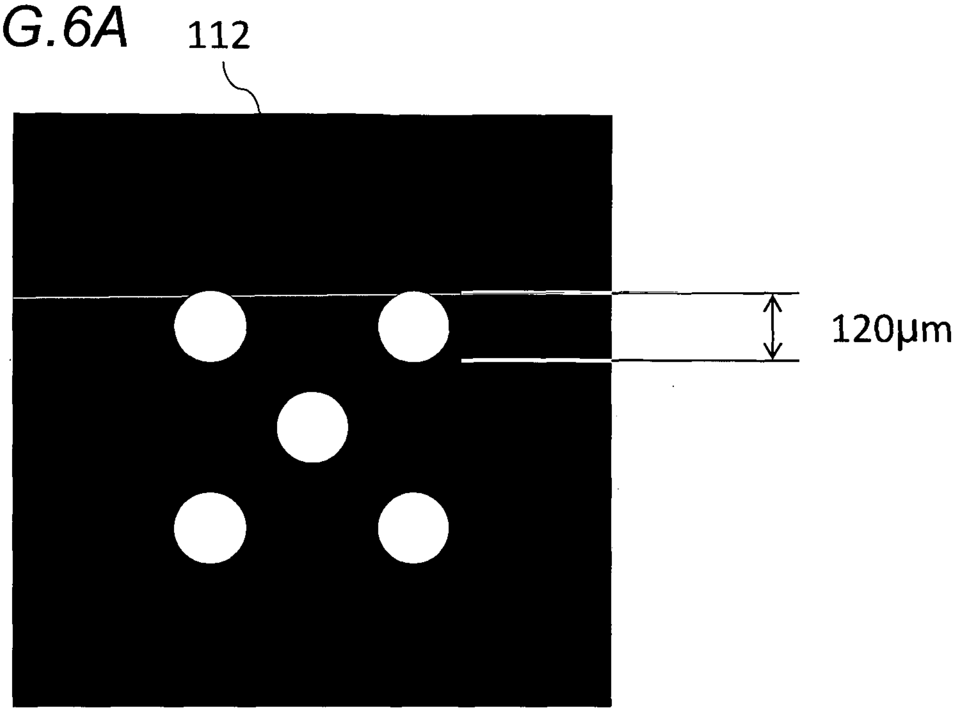
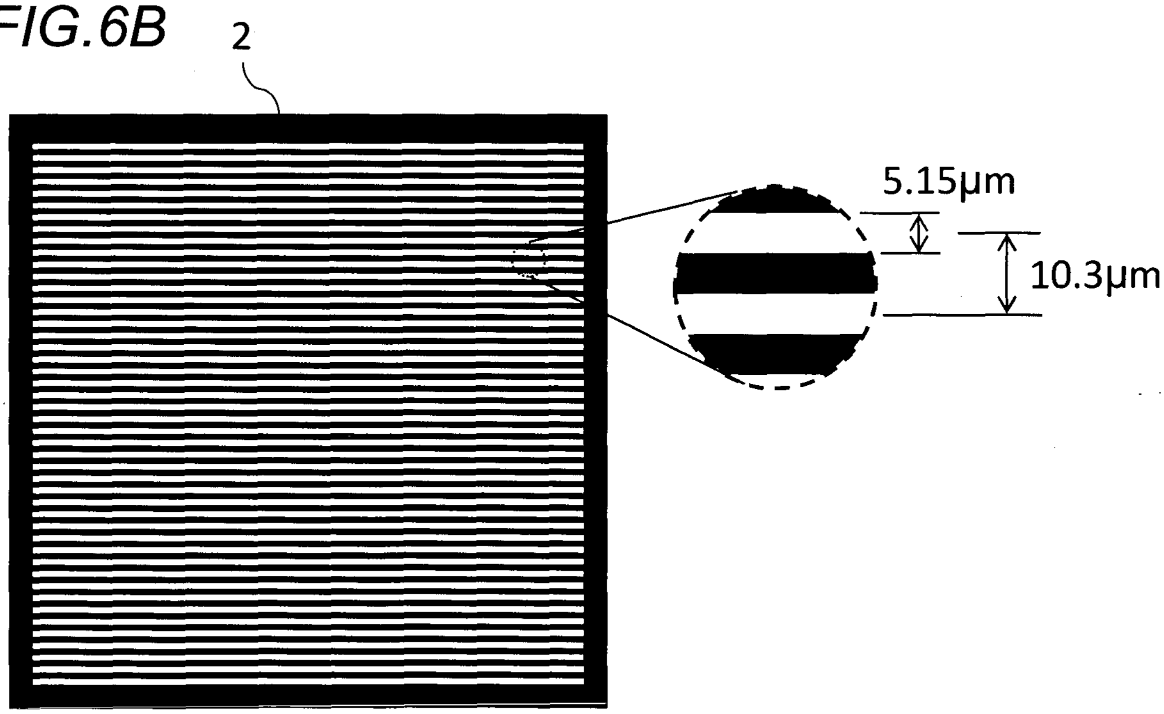


FIG.6B



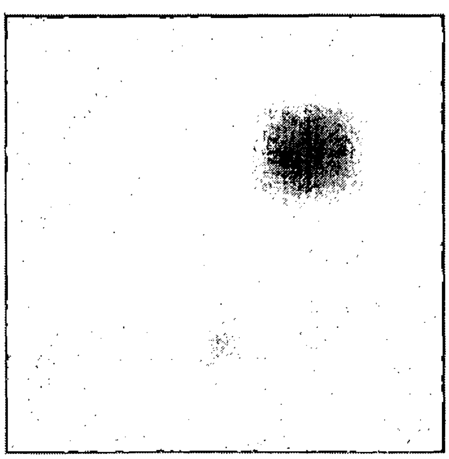


FIG.7A

FIG.7B

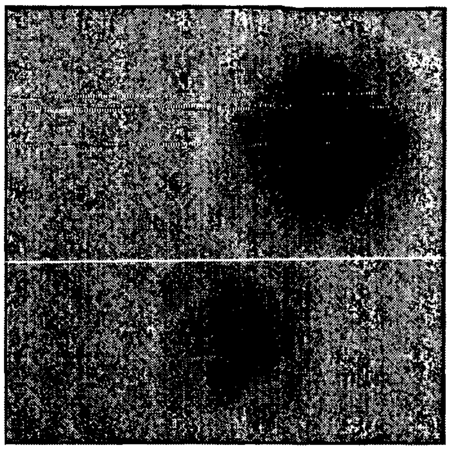


FIG.7C

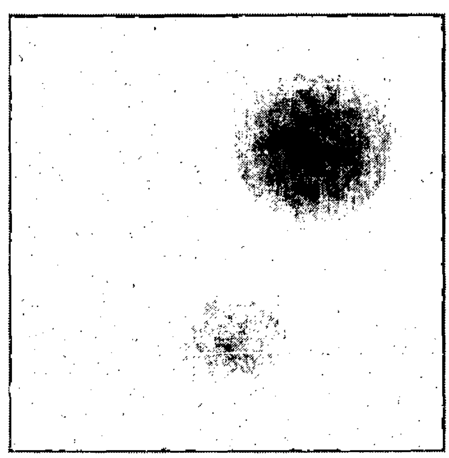


FIG.7D

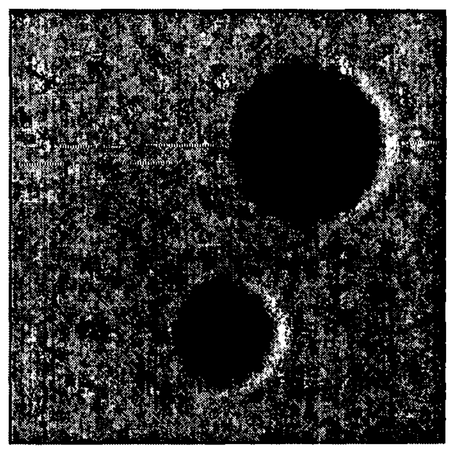


FIG.7E

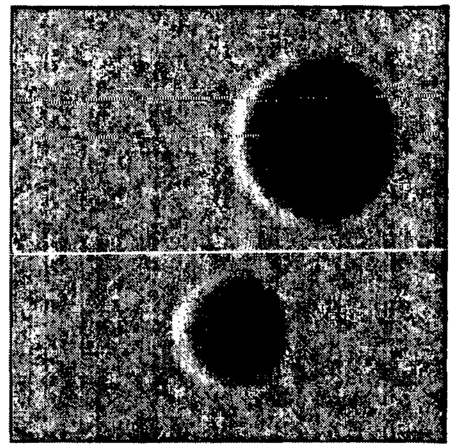


FIG.7F

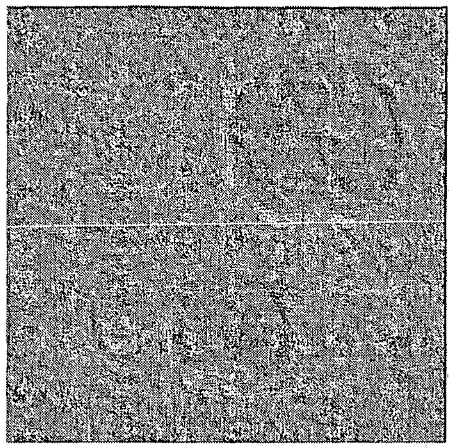


FIG.8C

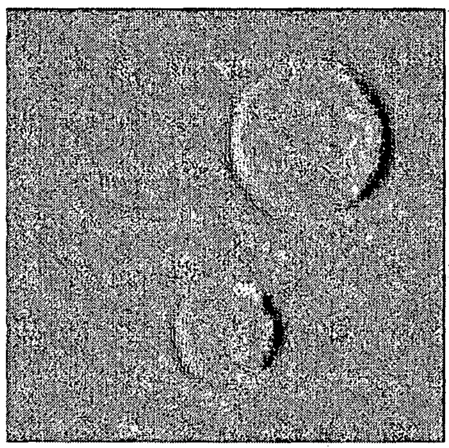


FIG.8B

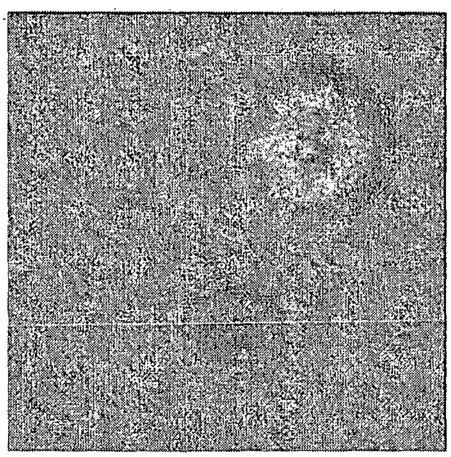


FIG.8A

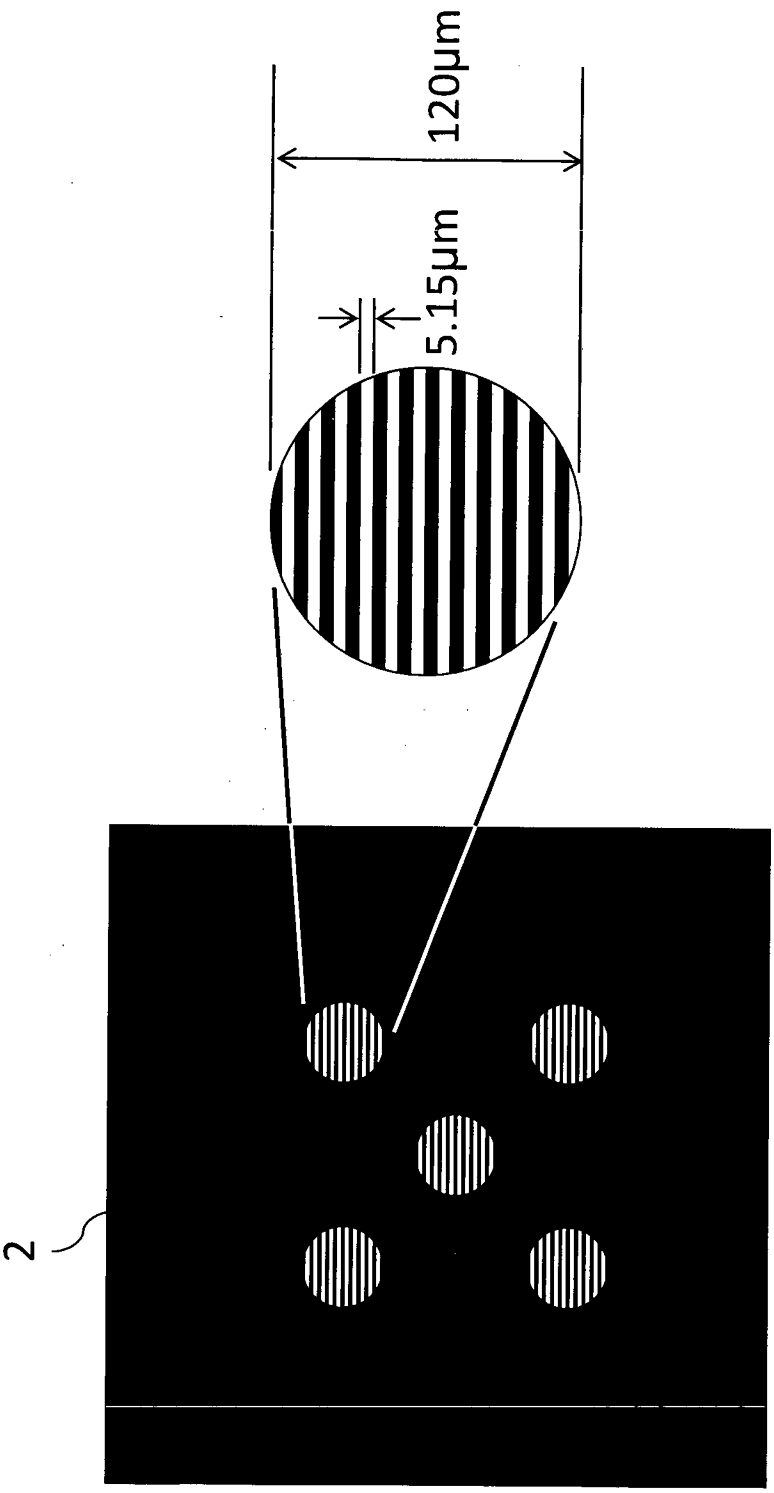


FIG.9

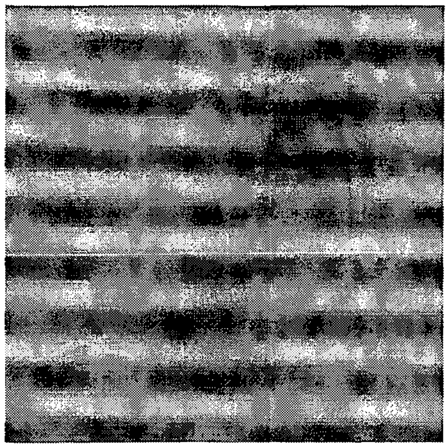


FIG.10C

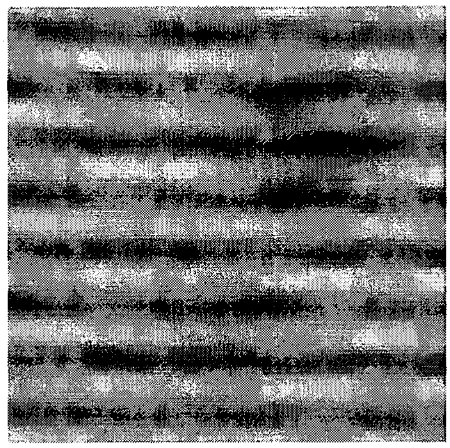


FIG.10B

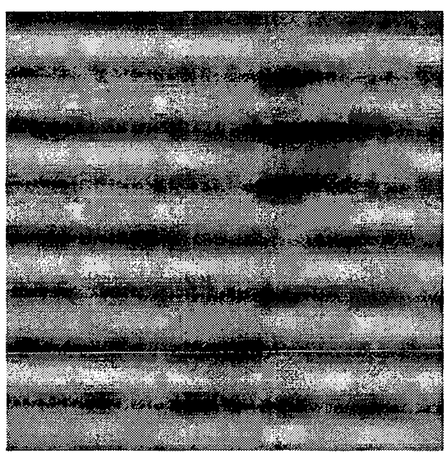


FIG.10A

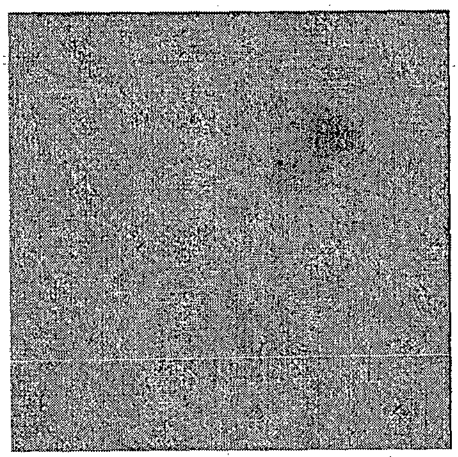


FIG.11A

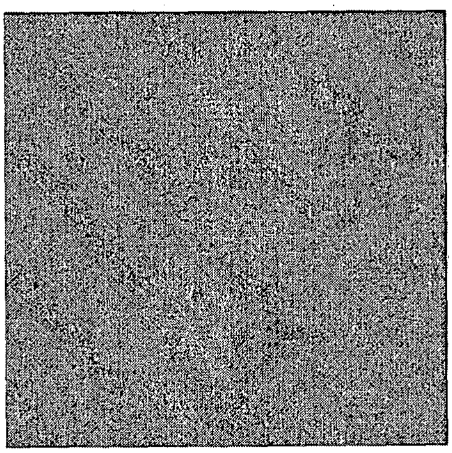


FIG.11B

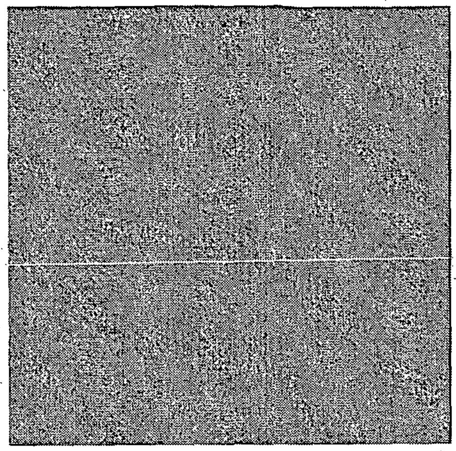


FIG.11C

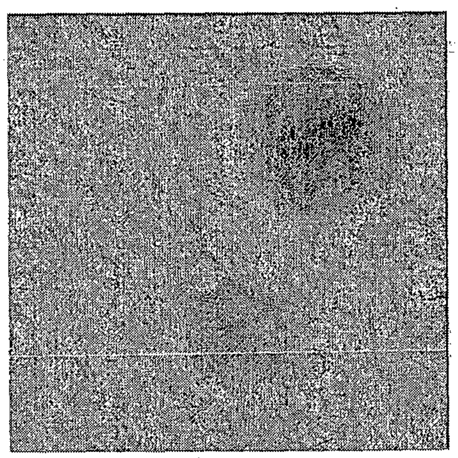


FIG.11D

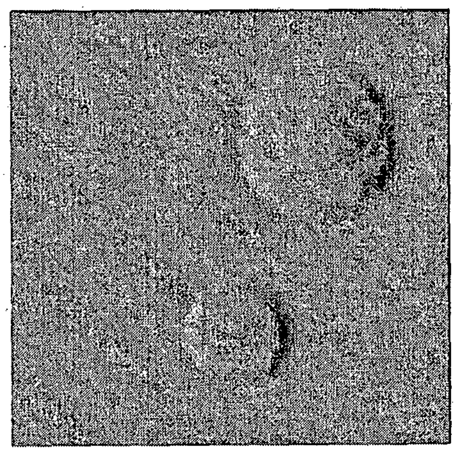


FIG.11E

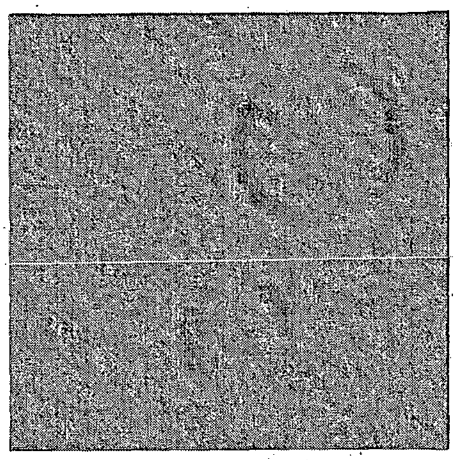


FIG.11F

INTERNATIONAL SEARCH REPORT

International application No
PCT/JP2014/074149

A. CLASSIFICATION OF SUBJECT MATTER
INV. G21K1/02
ADD.

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)
G21K H01J

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2010/150136 A1 (KONINKL PHILIPS ELECTRONICS NV [NL]; PHILIPS INTELLECTUAL PROPERTY [DE) 29 December 2010 (2010-12-29) figures 1,3 -----	1-15
A	US 7 920 673 B2 (LANZA RICHARD C [US] ET AL) 5 April 2011 (2011-04-05) cited in the application figure 10 -----	1-15
	-/--	

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

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
19 November 2014	28/11/2014

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

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DAMATO A L ET AL: "Coded Source Imaging for Neutrons and X-rays", 2006 IEEE NUCLEAR SCIENCE SYMPOSIUM CONFERENCE RECORD; 29 OCTOBER - 4 NOVEMBER 2006; SAN DIEGO, CA, USA, IEEE SERVICE CENTER, PISCATAWAY, NJ, USA, 29 October 2006 (2006-10-29), pages 199-203, XP002518083, DOI: 10.1109/NSSMIC.2006.356138 ISBN: 978-1-4244-0560-2 [retrieved on 2006-01-01] cited in the application the whole document -----	1-15

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/JP2014/074149

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
WO 2010150136	A1	29-12-2010	NONE		
US 7920673	B2	05-04-2011	US 2010027739	A1	04-02-2010
			WO 2009058976	A1	07-05-2009