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(54) **Efficient monochromator**

(57) The present invention relates to a monochromator (30) for monochromatizing a beam of γ-photons, x-ray photons having an energy higher than 10 keV or neutrons of an energy below 1 eV, wherein the monochromator (30) comprises a plurality of first (18a, 20a, 22a) and second (18b, 20b, 22b) Laue-crystals and refractive deflection means (24), said refractive deflection means (24) being arranged in series with said first Laue-crystals (18a, 20a, 22a).

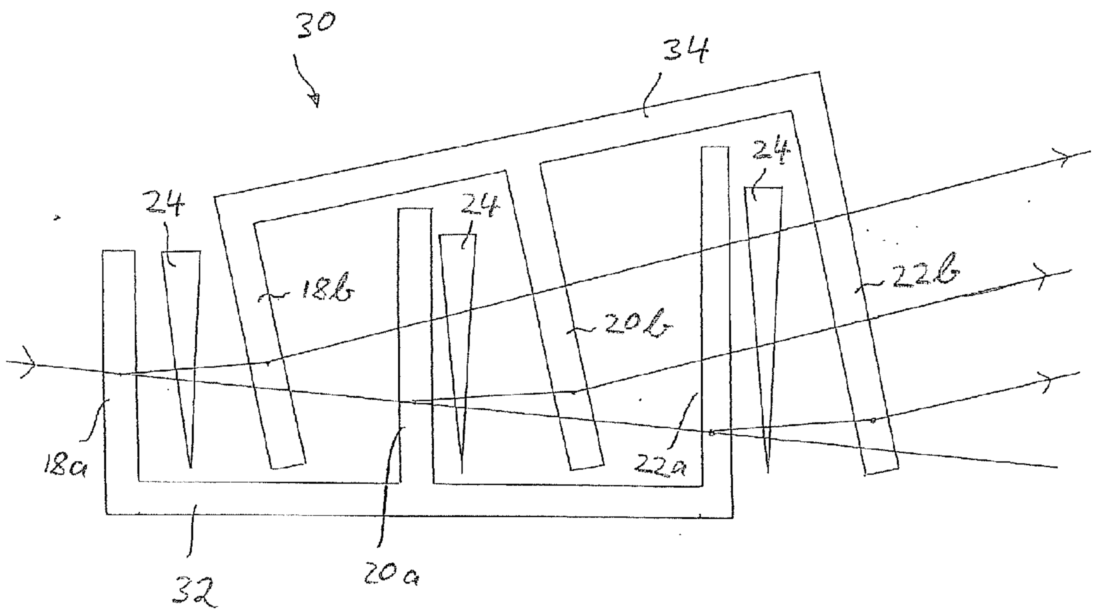

Fig. 6

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Description

FIELD OF THE INVENTION

[0001] The present invention is in the field of radiation physics. In particular, the present invention relates to an efficient monochromator comprising refractive deflection means and diffractive crystals.

RELATED PRIOR ART

[0002] To generate a monochromatic beam of x-ray photons, γ-photons or low energy neutrons, each referred to as "particles" in the following for brevity, the physical effect of "Bragg-reflection" or "Laue-diffraction" at a single crystal can be used. The Bragg-condition is known as $m \cdot \lambda = 2d \cdot \sin \theta$, where m is a positive or negative integer, d is the lattice spacing of the crystal, θ is the angle between the impinging beam and the lattice plane, and λ is the wavelength of the photon.

[0003] Note that "Laue-diffraction" is equivalent to "Bragg-reflection", except that the diffracted beam passes through the crystal rather than being reflected at the crystal surface. A Laue-diffraction can be regarded as a Bragg-reflection at crystal planes that are vertical to the crystal surface.

[0004] In particular, a Laue-crystal may be placed in the beam path of a primary beam of particles such that the Bragg-condition is fulfilled for particles of the desired energy. The particles of the desired energy are Laue-diffracted and leave the crystal under the diffraction angle while the remaining fraction of the beam is transmitted without diffraction. The diffracted beam is hence spatially separated from the primary beam and comprised of particles of a distinctive energy, i.e. it is monochromatized.

[0005] Monochromatization of a beam of particles can also be achieved in double crystal or Laue spectrometers. This is described for a beam of γ-photons in E.G. Kessler et al., Nucl Inst. Meth. A 457, 187 (2001*).* Such a Laue spectrometer is shown in Fig. 1 in two different geometries. The left part shows the two-crystal spectrometer 10 in the non-dispersive geometry, in which the first and second Laue-crystals 12, 14 are parallel to each other. The portion of the incoming particle beam that satisfies the Bragg-condition with regard to angle and wavelength, i.e. energy, is Laue-diffracted at the first Laue-crystal 12. This means that a certain angular spread of the incoming beam will still lead to a corresponding energy spread of the Bragg reflected beam. The remainder of the beam that does not satisfy the Bragg-condition will simply be transmitted without diffraction by the first Laue-crystal 12 (undiffracted transmitted beam not shown in Fig. 1). Since in the non-dispersive geometry the first and second Laue-crystals 12, 14 are parallel to each other, the crystal planes within the two crystals 12, 14 are parallel, too, and consequently all wavelengths that are diffracted by the first Laue-crystal 12 will simultaneously satisfy the Bragg-condition at the second Laue-crystal 14 and will be diffracted likewise.

[0006] In the right part of Fig. 1, however, the second Laue-crystal 14 is inclined with regard to the first Laue-crystal 12 by twice the Bragg angle of a given wavelength λ. This means that at the second Laue-crystal 14, only particles with the corresponding wavelength λ will be Laue-diffracted. However, particles deviating from λ that have been Laue diffracted by the first Laue-crystal 12 do no longer meet the Bragg-condition at the second Laue-crystal 14 and will therefore be transmitted without diffraction by the second Laue-crystal 14 (undiffracted transmitted beam not shown). Accordingly, in the dispersive mode, the two-crystal spectrometer 10 acts as a monochromator, since the particles which are Laue-diffracted by the second Laue-crystal 14 are within a very narrow energy band. For example, the monochromatization, which is equivalent to the relative energy width ΔE/E of a γ-beam in a Laue spectrometer in dispersive geometry is typically 10^{-6}.

[0007] When the second crystal 14 is rotated stepwisely through a small angular range, the intensity profile of the twice diffracted beam can be recorded as a function of the rotation angle. This measured intensity profile is also referred to as "rocking curve" due to the "rocking" movement of the crystal. Within dynamical diffraction theory, it can be shown that for so-called perfect single crystals, the width of the rocking curve I(Θ) is proportional to λ meaning that the intensity-angle-profile is very narrow for large energies. Example calculations of I(Θ) for a 2.5 mm thick single crystal of Si in [220] orientation are shown in Fig. 2 for photons of 100 keV, 500 keV and 1000 keV. As can be seen, the width of theses curves decreases with energy and can be as small as a few tens of nanoradiants (nrad).

[0008] The width of I(Θ) can be called the "acceptance witdh" of the single crystal, since it defines an angular range for particles of the given wavelength λ that will be "accepted" by the crystal in the sense that they are Laue-diffracted thereby. Conversely, this means that radiation impinging at an angle outside this acceptance range will not be Laue-diffracted by the first Laue-crystal 12, even if it has the desired energy (the appropriate wavelength λ) and will hence be lost for the monochromator of Fig. 1. For example, the best collimated γ-beams typically have a divergence in the range of tens of microrad, which means that actually the biggest part of the impinging γ-beam will fall outside the angular acceptance range and hence will be lost for the monochromator, resulting in a very low efficiency.

SUMMARY OF THE INVENTION

[0009] The problem underlying the invention is to provide a monochromator of improved efficiency for monochromatizing a beam of γ-photons, x-ray photons having an energy higher than 10 keV and neutrons of an energy below 1 eV. This problem is solved by the monochromator of claim 1. Preferred embodiments are defined in the dependent claims.
[0010] The monochromator according to the present invention comprises a plurality of pairs of Laue-crystals, each pair of Laue-crystals having

- a first Laue-crystal for diffracting a portion of an incoming beam that meets the Bragg-condition and transmitting the remainder of the incoming beam without diffraction, and
- a second Laue-crystal arranged with respect to the first Laue-crystal such as to allow for a further Laue-diffraction of the beam portion that was Laue-diffracted at the first Laue-crystal of said pair of Laue-crystals.

[0011] Herein, the first Laue-crystals of all pairs of Laue-crystals are parallel to each other and the second Laue-crystals of all pairs of Laue-crystals are parallel to each other as well. The first Laue-crystals of the pairs of Laue-crystals are arranged in series with refractive deflection means arranged inbetween such that the part of the beam that is transmitted without diffraction by one of said first Laue-crystals is deflected prior to impinging on the next first Laue-crystal in said series of first Laue-crystals. Accordingly, the part of the beam that is transmitted without diffraction by one of the first Laue-crystals — because it may be outside the angular acceptance range of said first Laue-crystal — is deflected prior to impinging on the next first Laue-crystal in said series. This deflection will lead to a shift of the transmitted undiffracted beam in angular space before impinging on the next first Laue-crystal. Since all first Laue-crystals are parallel to each other, a portion of the beam that was transmitted without diffraction by the previous first Laue-crystal will now fall into the angle acceptance range and will be Laue-diffracted by the next first Laue-crystal in the series and — after further Laue-diffraction at the corresponding second Laue-crystal of the pair — contribute to the monochromatized beam. Accordingly, for the same incident beam, the efficiency of the monochromator is (except for absorption losses) increased over that of an ordinary Laue spectrometer by a factor corresponding to the number of Laue-crystal pairs.
[0012] Preferably, the refractive deflection means arranged between consecutive first Laue-crystals in said series of first Laue-crystals are adapted to deflect the beam by an angle α that is larger than but still reasonably close the angular acceptance width of the first Laue-crystal for the desired particle energy. In particular, the angle α is given by 5 nrad < α < 200 nrad, preferably 10 nrad < α < 100 nrad.
[0013] In a preferred embodiment, the number of pairs of Laue-crystals employed in the monochromator is at least 5, preferably at least 10 and more preferably at least 50. The higher the number of pairs of Laue-crystals, the larger is the efficiency of the monochromator. In practice, one will have to find a suitable compromise between optimum efficiency and structural effort.
[0014] Preferably, the first and second Laue-crystals of each pair of Laue-crystals are either parallel to each other, which corresponds to the non-dispersive mode, or inclined with respect to each other such as to allow for an energy selection by two consecutive Laue diffractions, and in particular inclined by twice the Bragg-angle of the desired wavelength. This corresponds to the dispersive geometry. In practice, the dispersive geometry is preferably used for monochromatization, while the non-dispersive mode may be used to align all optical elements, in particular the deflection means. In a particularly preferred embodiment, the first and second Laue-crystals are shiftable between the two configurations. This will for example allow precisely adjusting the refractive deflection elements in the non-dispersive (parallel) mode and then decreasing the energy width by shifting the first and second Laue-crystals with respect to each other to the dispersive geometry.
[0015] In a preferred embodiment, all first Laue-crystals are part of one fixed first unit, and all second Laue-crystals are part of one fixed second unit. Herein, the first and second units are preferably each made from a single crystal block, as this ensures that all first crystals and all second crystals are mutually parallel with each other.
[0016] In a preferred embodiment, both blocks are taken from the same ingot, which allows for a perfect match of the first and second Laue-crystals. The Laue-crystals may in particular consist of Si and/or Ge. Also, preferably a collimating lens, lens stack or lens array is arranged upstream of the monochromator such as to parallelize or at least reduce the divergence of the beam prior to entering the monochromator. This way, the efficiency of the monochromator can be dramatically increased. Herein, collimating lenses, lens stacks or lens arrays may be employed.
[0017] From a conceptional point of view, it is easiest to think of the monochromator as a series of completely separate Laue-spectrometers, where each beam transmitted without diffraction by the first Laue-crystal of a given Laue-spectrometer is deflected and then inputted into the first Laue-crystal of the following Laue-spectrometer. However, since the angle between beams transmitted undiffracted by and Laue-diffracted by a Laue-crystal will be very small, a spatial separation of the pairs of Laue-crystals will in practice be difficult to achieve. Instead, in practice the geometry will rather be such that a beam that has already been Laue-diffracted by a first (second) Laue-crystal of one pair passes a first (second) Laue-crystal of another pair of Laue-crystals, becauseit is difficult to keep these Laue-crystals of the further

pair out of the way of the diffracted beam. However, since all first (second) Laue-crystals are parallel to each other, this would imply that the already Laue-diffracted beam is Laue-diffracted at the fist (second) Laue-crystal of this other pair of Laue-crystals again. According to an embodiment of the invention, this is prevented by ensuring that a beam that has already been Laue-diffracted by a first (second) Laue-crystal of one pair is deflected using a refractive optical element prior to passing a first (second) Laue-crystal of another pair of Laue-crystals. This way, it can be ensured that the beam is diffracted only once at a first Laue-crystal and once at a second Laue-crystal forming the abovementioned pair of Laue-crystals.

[0018] In one embodiment, the refractive optical elements arranged between two adjacent first Laue-crystals for deflecting a beam transmitted without diffraction by the previous first Laue-crystal in said series are arranged to also deflect the beam that is Laue-diffracted by said previous first Laue-crystal. Accordingly, this way it can be ensured that the Laue-diffracted beam is not Laue-diffracted at any further first Laue-crystal in said series, because after deflection, i.e. an angle change, it no longer obeys the Bragg-condition.

[0019] In a preferred embodiment, the first and second Laue-crystals are arranged in the monochromator such that the first and second Laue-crystals of each pair are adjacent to each other.

[0020] In an alternative embodiment, the first and second Laue-crystals are arranged in the monochromator such that all first Laue-crystals are arranged in a series and all second Laue-crystals are arranged in a further series that is arranged downstream of the series of first Laue-crystals with regard to the propagation direction of the beam. Further, first refractive deflection means are placed between each two neighbouring first Laue-crystals, and second refractive deflection means are placed between each two neighbouring second Laue-crystals. Herein, the second refractive deflection means in the n^{th} gap between neighbouring second Laue-crystals when counted in opposite propagation direction of the beam is adapted to compensate for the deflection provided by the first refractive deflection means in the n^{th} gap between neighbouring first Laue-crystals when counted in propagation direction of the beam. With this geometry, each beam that is Laue-diffracted at any first Laue-crystal may pass through all downstream first and second Laue-crystals while it is still ensured that it is only Laue-diffracted by the corresponding second Laue-crystal of the pair. As will be explained in more detail below with reference to a preferred embodiment, in this geometry, the most upstream one of the first Laue-crystals and the most downstream one of the second Laue-crystals form a pair, the second most upstream one of the first Laue-crystals and the second most downstream one of the second Laue-crystals form a further pair and so on.

[0021] As explained above, refractive deflection means are employed in preferred embodiments of the monochromator to ensure that at a distinctive Laue-crystal the Bragg-condition is or is not fulfilled. Different refractive optical elements, for example a collimating lens, may be arranged upstream of monochromator for a further increase of efficiency as mentioned above. While it is known to manipulate x-ray beams using refractive optical elements, it is so far generally accepted that at photon energies above say 200 keV, this is no longer possible. The reason is that according to the present understanding in the art, the index of refraction, which even in the x-ray regime is already very close to 1, rapidly converges even closer to 1 with increasing energy. The index of refraction n is usually written as $n = 1 + \delta + i\beta$, where δ is the deviation of the real part of n from unity. In the x-ray regime, the physical effect giving rise to δ is the virtual photo effect (Rayleigh scattering), which is therefore also referred to as "δ_{photo}" in the following. In the x-ray regime, δ_{photo} is negative, i.e. the index of refraction n is smaller than 1. A typical value of δ_{photo} at 80 keV and aluminum is -0.8×10^{-7}. Accordingly, the person skilled in the art would not have believed that it would be possible to use the monochromator design according to one of the above embodiments for energies well above say 200 keV, because according to common wisdom, a sufficient refractive deflection as required in the monochromator at these energies would have been considered impossible.

[0022] However, according to the priority document EP 11 188 251 of the present invention, which is hereby included by reference, the inventors have found in very precise and quite involved experiments that surprisingly, for energies beyond some threshold, the value of δ increases again and in fact acquires a positive value. In other words, for photon energies above said threshold, the index of refraction is > 1 again, and the value of δ, i.e. the difference of n from unity, is large enough to allow for the design of useful refractive optical elements. For Si, experiments demonstrate that at about 700 keV, δ becomes positive and in fact acquires a value that is sufficiently large to allow for the design of useful refractive optical elements.

[0023] Further, the inventors have been able to attribute the unexpected positive δ beyond 700 keV (for Si) to a virtual pair creation, which has also been referred to as "Delbrück scattering" in the literature. This result is surprising as well, since in earlier works by J. S. Toll und J. A. Wheeler, it has been predicted that for energies of 1 MeV the contribution of the virtual pair creation to the absolute value of δ was about a factor 10^3 smaller than the contribution due to the virtual photo effect (Rayleigh scattering) and should hence have a negligible effect on the index of refraction (see J.S. Toll; The Dispersion Relation for Light and the Applications involving Electron Pairs, Princeton University (1952*) unpublished).*

[0024] The pivotal result of the findings of the inventors is hence that at energies beyond some threshold of say a few hundred keV, the index of refraction will sufficiently deviate from unity such as to allow for refractive optical elements that can be used for shaping or deflecting a γ-beam. This means that the monochromator according to one of the above embodiments can even be used in the γ-regime, because contrary to common wisdom, refractive optical elements are possible even at such high energies.

[0025] When using the one or more refractive optical elements in the γ-regime, the use employs the fact that the index of refraction n of the optical material has a real part > 1, or, in other words, that $\delta > 0$. This means that the design of the optical elements will be different from refractive x-ray optical elements and conceptually in fact more similar to ordinary light optics. For example, when using refractive optical elements for γ-photons having an energy of more than 700 keV, a focusing lens would have a convex shape, whereas an x-ray focusing lens has a concave shape. Suitable novel means for collimation and deflection which may be used with the monochromator in an embodiment for specific use in the γ-regime will be described below.

[0026] In a preferred embodiment, the refractive deflection means for deflecting the beam is comprised by an array of prisms, wherein the array of prisms comprises at least one series arrangement of prisms allowing for being consecutively passed by a beam. By arranging a plurality of prisms in series, the minute deflections occasioned by each individual prism add up to provide for a considerable total deflection by the array of prisms as a whole.

[0027] Preferably, a number N of prisms are arranged in series, such as to be consecutively passed by a beam. Herein, N may be ≥ 2, preferably ≥ 10 and more preferably ≥ 100. The suitable number of N also depends on the angle of the prism. However, if desired, the number of prisms arranged in series can be easily increased to hundreds or even thousands, in view of the comparatively small absorption of γ-radiation in matter.

[0028] Preferably, at least the majority of prisms in the array of prisms has a wedge-shape with a base surface having a triangular shape. Herein, the height of the triangular shape is preferably smaller than 200 μm, preferably smaller than 50 μm. The base surface may further have an isosceles triangle shape, wherein the angle γ between the two equal sides of said isosceles triangle is preferably between 5° and 120°, more preferably between 15° and 90°.

[0029] In a preferred embodiment, the array of prisms may also comprise a number M of series arrangements of prisms arranged in parallel, wherein $M \geq 2$, preferably $M \geq 4$ and more preferably $M \geq 10$. This allows deflecting a large diameter beam with a suitably large number of series arrangements of comparatively small prisms arranged in parallel.

[0030] The array of prisms is preferably at least in part made from one or more wafers, in particular Si and/or Ge wafers, in which the prisms are formed by etching. Herein, the one or more wafers has/have a thickness between 20 μm and 200 μm, preferably between 50 μm and 100 μm, and the array of prisms may at least in part be made from a stack of a plurality of identically etched wafers wherein said wafers of said stack are preferably grown or fused together such as to yield a total thickness of the stack of 5 mm or more, preferably 8 mm or more.

[0031] In a preferred embodiment for operation in the γ-regime, the above mentioned collimating lens to reduce the divergence of the beam prior to entering the monochromator has at least one, preferably two lens surfaces having a convex shape in two dimensions, and in particular, a rotation-ellipsoid shape. Such lens is referred to as a 2-D-lens, as it can collimate a γ-beam in two dimensions. In a preferred embodiment, the convex lens is made from an embossed foil comprising one of Be, Al, Ni, Ta or Th as its main constituents. By embossing the foil, two-dimensional lenses can be manufactured easily and efficiently and with great precision of about 5 nm. Alternatively, such 2-D-γ-lens could also be made by micromachining.

[0032] Preferably, the tangential radius R at the apex of the lens is < 2000 μm, preferably < 1000 μm and more preferably between 5 μm and 500 μm. However, for contracted γ-beams, even smaller radii down to 1μm can be used.

[0033] Preferably, a number N of said convex lenses are arranged in series, for example stacked one behind the other in a lens holder. Herein, N is preferably between 2 and 10000, more preferably between 10 and 200. By stacking a large number of such convex lenses in series, a moderate focal length of the total stack of lenses can be achieved in spite of the rather small value of δ, thereby allowing for an efficient collimation of γ-beams. Since the absorption of γ-radiation is much less than that of x-ray radiation, the number of optical elements that can be arranged in series such as to accumulate the refractive effect of the individual refractive optical elements but still at a moderate total absorption is much higher for γ-radiation than for x-ray radiation.

[0034] Preferably, the body of said lens has a hole for ventilation, to thereby prevent the formation of air cushions and to avoid bending of the lens when mounting the lens array. The shape of the hole is not limited, as long as it allows for sufficient ventilation.

[0035] In a preferred embodiment, the divergence of the γ-beam prior to entering the monochromator is reduced by an array of lenses, wherein said array of lenses comprises at least one series arrangement of lenses allowing for being consecutively passed by a γ-beam, and wherein at least the majority of the lenses has at least one, preferably two lens surfaces having a convex shape in at least one dimension. For example, the "series arrangement" of lenses could be an arrangement of lenses along their optical axes. The term "lens surface" refers to the "entrance surface" and "exit surface" of the lens.

[0036] Herein, the mean radius of curvature of the convex shape or the tangential radius at the apex of the convex shape is preferably between 1 μm and 500 μm, preferably between 10 μm and 80 μm. Note in this regard that for manufacturing purposes, the convex lens surface may have a conical shape (in case of a 2-D-lens) or a triangular prism-like shape (in case of a 1-D-lens), in which case no tangential radius at the apex of the convex shape is defmed, but a prism angle instead. In this case, we refer to the mean radius of curvature of the convex shape, which is defined as the radius of an arch or a sphere containing the apex and an edge portion of the lens surface.

[0037] Preferably, in the series arrangement, a number N of lenses are arranged in series such as to be consecutively passed by a γ-beam, wherein $N \geq 10$, preferably $N \geq 100$ and more preferably, $N \geq 300$. In some applications N may even be ≥ 1000. As before, by arranging a large number of lenses in series, the refractive power of the individual lenses adds up and the focal length of the total array is decreased.

[0038] Preferably, the array of lenses comprises a number M of series arrangements of lenses arranged in parallel, wherein $M \geq 2$, preferably $M \geq 4$ and more preferably $M \geq 10$. By providing a plurality of series arrangements of lenses in parallel, it is possible to shape a γ-beam having a beam diameter that is considerably larger than the diameter of each individual lens. Note in this regard that due to the comparatively small radius of curvature of the lenses, the diameter of each individual lens will likewise be comparatively small. However, by arranging a plurality of series arrangements of lenses in parallel, an arbitrarily large beam cross section can be split up into a plurality of individual beamlets that are independently focused, collimated or shaped in another suitable way. The individually focused beamlets can then be further shaped, for example be deflected to be focused on a single spot or area, as is explained in more detail below.

[0039] In a preferred embodiment, the lens array is at least in part made from one or more wafers, in particular Si and/or Ge wafers, in which the lens surfaces are formed by etching. As is shown in detail in the experimental section below, both Si and Ge provide a sufficient index of refraction to construct useful refractive optical elements therefrom. While there are elements that would actually lead to a larger index of refraction, the advantage of using Si and/or Ge is that one can resort to well-established lithography and etching technology, in particular electron beam lithography, to efficiently and precisely manufacture miniature structures, thereby allowing to manufacture arrays of very large numbers of lenses with a very small radius of curvature in a cost efficient way. Also, due to this manufacturing, the individual lenses can be aligned very precisely.

[0040] Preferably, the one or more wafers has/have a thickness between 20 μm and 200 μm, preferably between 50 μm and 100 μm. If the thickness is below 100 μm, it is possible to etch precise vertical walls constituting the lens surfaces, for example by ion beam deep etching or the like. Note that alternative manufacturing methods, including improved methods that will become available in the future are also possible.

[0041] In a preferred embodiment, the lens array is at least in part made from a stack of a plurality of identically etched wafers, wherein the wafers of the stack are preferably grown or fused together. This allows obtaining a total thickness of the stack of wafers of for example 5 mm or more, preferably 8 mm or more, thereby allowing to shape a γ-beam having a corresponding beam width. If desired, even larger stacks of identically etched wafers can be formed.

[0042] Owing to the vertical etching technique, the lens surfaces have a convex shape only in one dimension, i.e. are 1-D lenses only. This means that the lens array can only focus a γ-beam in the plane of the wafer but not in a plane perpendicular to the wafer plane. However, in a preferred embodiment, the γ-beam is focused or collimated by two arrays of lenses according to one of the embodiments described above, which are arranged in series and are oriented with respect to each other such that each of the two lens arrays focuses or collimates a γ-beam within different planes, such as two perpendicular planes.

SHORT DESCRIPTION OF THE FIGURES

[0043]

Fig. 1	shows a schematic view of a double crystal spectrometer in the non-dispersive and dispersive mode.
Fig. 2	shows examples of rocking curves at energies of 100 keV, 500keV and 1000 keV for a 2.5 mm Si crystal.
Fig. 3	is a schematic representation of a monochromator according to one embodiment of the invention.
Fig. 4	is a series of diagrams showing intensity-angle profiles of a beam in various places within the monochromator of Fig. 3.
Fig. 5	is a schematic angle-energy diagram illustrating the operation of a monochromator according to an embodiment of the invention.
Fig. 6	is a schematic sectional view of a monochromator according to a further embodiment of the invention.
Fig. 7	is a schematic sectional view of a further embodiment of the monochromator of the invention.

Fig. 8 is a schematic perspective view showing one of the crystal units of the monochromator of Fig. 7.

Fig. 9 (a) and (b) show a plan view and a perspective view of a wedge array according to an embodiment of the present invention.

Fig. 10(a) and (b) show a cross sectional view and a perspective view of a 2-D lens according to an embodiment of the invention.

Fig. 11 (a) and (b) show a plan view and a perspective view of a lens array according to an embodiment of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0044] For the purposes of promoting an understanding of the principles of the invention, reference will now be made to the preferred embodiments illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended, such alterations and further modifications in the illustrated devices and methods and such further applications of the principles of the invention as illustrated therein being contemplated as would normally occur now or in the future to one skilled in the art to which the invention relates.

[0045] Fig. 3 is a schematic representation of a monochromator 16 according to an embodiment of the present invention. The monochromator 16 comprises three pairs of Laue-crystals, 18a/18b, 20a/20a, 22a/22b which in combination each form a two-crystal spectrometer 10 in the dispersive geometry as shown on the right hand side of Fig. 1. All the first Laue-crystals 18a, 20a, 22a of all pairs of Laue-crystals 18a/18b, 20a/20a, 22a/22b are parallel to each other. Likewise, all the second Laue-crystals 18b, 20b, 22b of all pairs of Laue-crystals 18a/18b, 20a/20a, 22a/22b are parallel to each other. The first Laue-crystals 18a, 20a, 22a of the pairs of Laue-crystals 18a/18b, 20a/20a, 22a/22b are arranged in series with refractive deflection means 24 arranged inbetween neighbouring first Laue-crystals 18a, 20a, 22a such that the part of the beam that is transmitted without diffraction by one of the first Laue-crystals 18a, 20a is deflected prior to impinging on the next first Laue-crystal 20a, 22a in the series. While the refractive deflection means 24 is symbolically represented by a wedge prism 24 in Fig. 3, it is understood that in practice the wedge arrays as described for example further below with reference to Fig. 9 will be employed.

[0046] Next, the function of the monochromator 16 of Fig. 3 is explained with reference to Fig. 4. Panel A of Fig. 4 shows the intensity-angle profile of the incoming beam impinging on the first Laue-crystal 18a of the first pair of Laue-crystals 18a/18b. Only the portion of the beam that fulfils the Bragg-condition with respect to the first crystal 18a will be Laue-diffracted at the first Laue-crystal 18a. However, most of the beam will actually not meet the Bragg-condition and hence be transmitted without diffraction through the first crystal 18a of the first pair of Laue-crystals 18a/18b. This is indeed seen from panel B of Fig. 4, which shows the intensity-angle profile at location Ⓑ of Fig. 3, i.e. the intensity-angle profile of the beam that was transmitted without diffraction through the first Laue-crystal 18a. As is seen in panel B of Fig. 4, a small angular band of the intensity is missing, corresponding to the narrow angular band that has been Laue-diffracted by the first Laue-crystal 18a.

[0047] Next, the part of the beam transmitted without diffraction by the first Laue-crystal 18a passes the refractive deflection means 24. Panel C of Fig. 4 shows the intensity-angle profile at position © just behind the refractive deflection means 24. As is seen from panel C of Fig. 4, the shape of the intensity-angle profile has not changed, but it has been shifted in angle space due to the refractive deflection means 24. Next, the beam with the shifted intensity-angle profile impinges onto the first Laue-crystal 20a of the second pair of Laue-crystals 20a/20b. Due to the angular shift of the intensity profile, the beam now contains a portion obeying the Bragg-condition with regard to angle and energy again, allowing for a further Laue-diffraction at the first Laue-crystal 20a of the second pair of Laue-crystals 20a/20b. Note in this regard that since all first Laue-crystals 18a, 20a, 22a of each pair of Laue-crystals 18a/18b, 20a/20b, 22a/22b are parallel to each other, the angular acceptance range for Laue-diffraction is always the same. However, due to deflection by the refractive deflection means 24, a portion of the beam energy that was outside the acceptance range of the previous first Laue-crystal (in this case 18a) and was hence transmitted without diffraction may now be shifted into the acceptance range and will be Laue-diffracted (in this case at 20a).

[0048] This is seen from panel D of Fig. 4, which shows the intensity-angle profile at location Ⓓ right behind the first Laue-crystal 20a of the second pair of Laue-crystals 20a/20b. As is seen from panel D of Fig. 4, a second angular band is missing in the intensity profile of the transmitted undiffracted beam, which corresponds to the portion of the beam that has been Laue-diffracted at the first Laue-crystal 20a of the second pair of Laue-crystals 20a/20b.

[0049] This procedure can be repeated with many pairs of Laue-crystals, where in each case the part of the beam that is transmitted without diffraction by the previous first Laue-crystal is deflected prior to impinging on the next first Laue-crystal in the series. Since only the Laue-diffracted portion of the beam adds to the output of the monochromator 16, it is seen that the efficiency of the monochromator 16 is thereby increased. When neglecting the losses within the multiple pairs of Laue-crystals and the refractive deflection means, the efficiency is generally proportional to the number of pairs of Laue-crystals.Herein, it is advantageous for γ-beams that the absorption of γ-rays in matter is very low compared for example to the absorption of x-rays.

[0050] The efficiency increase is further illustrated with reference to Fig. 5 which schematically shows the energy and angular distribution of the beam entering the monochromator 16. If only a single pair of Laue-crystals was used, only a small section of the angle-energy range of the impinging beam will be Laue-diffracted, which is schematically indicated by the small square 26 in Fig. 5. Namely, the small area 26 corresponds to the part of the angle-energy distribution that satisfies the Bragg-condition at the first Laue-crystal 18a, while the rest of the beam is transmitted without diffraction by the first Laue-crystal 18a and would be lost in an ordinary double-crystal spectrometer. However, by consecutively deflecting the beam transmitted without diffraction by the previous first Laue-crystal 18a, 20a, 22a, generally the full band 28 of desired energies can be consecutively harvested from the beam, thereby increasing the efficiency of the monochromator 16.

[0051] Note that in the illustration of Fig. 3, the deflection of the beam by the refractive deflection means 24 has not been shown. The reason is that the angular shift of the intensity profile that is needed to "refill" the angular acceptance range is very small, since the angular acceptance range is very narrow. In principle, it is sufficient to provide for a shift that is slightly larger than the width of the acceptance range.

[0052] While the geometry of the monochromator 16 of Fig. 3 is particularly useful for explaining the inventive concept underlying the monochromator of the present invention, with regard to the practical implementation it is not the currently preferred embodiment. Note in this regard that the Bragg-angles of the Laue-diffraction have been illustrated extremely exaggerated in Fig. 3. In reality, the angular split between the undiffracted transmitted and the Laue-diffracted beams in practice is very small. Accordingly, while in Fig. 3 a beam that has already been Laue-diffracted by the first Laue-crystal, such as crystal 18a, avoids any further first Laue-crystal downstream thereof (such as Laue-crystal 20a), in view of the small angular separation between undiffracted transmitted and diffracted beams this may be difficult to achieve. Likewise, in the geometry of Fig. 3, the beam that is Laue-diffracted at the second Laue-crystal 18b of the first pair of Laue-crystals 18a/18b does not pass through the second Laue-crystal 20b of the second pair of Laue-crystals 20a/20b. However, if this was the case, then the beam diffracted by the second Laue-crystal 18b would be Laue-diffracted at the second Laue-crystal 20b again, which is not desired. Instead, it is intended that in the monochromator 16, each beam of the desired energy is Laue-diffracted exactly once at a first Laue-crystal 18a, 20a, 22a and once at a corresponding second Laue-crystal 18b, 20b, 22b. This can indeed be achieved even if the Laue-diffracted beam passes through multiple further Laue-crystals of the same kind, if it is ensured that a beam that has already been Laue-diffracted by a first (second) Laue-crystal of one pair of Laue-crystals is deflected using refractive deflection means prior to passing a first (second) Laue-crystal of another pair of Laue-crystals. Namely, due to the angle change in the deflection, the already diffracted beam does no longer obey the Bragg-condition if passing a Laue-crystal of the same kind (first or second) later on and hence will not be Laue-diffracted again.

[0053] An example of such an arrangement is shown in the monochromator 30 of Fig. 6. In Fig. 6, again three pairs of Laue-crystals 18a/18b, 20a/20b, 22a/22b and refractive deflection means 24 are shown. In the embodiment of Fig. 6, all first Laue-crystals 18a, 20a, 22a are part of a (fixed) first unit 32 that is made from a single crystal block. Likewise, all second Laue-crystals 18b, 20b and 22b are part of one fixed second unit 34 and are also made from a single crystal block. This way, it is ensured that all first Laue-crystals 18a, 20a, 22a and all second Laue-crystals 18b, 20b, 22b are parallel with each other, respectively. Preferably, both units 32 and 34 are taken from the same ingot, so that the lattice structures ideally match.

[0054] In the monochromator 30 of Fig. 6, the refractive deflection means 24 arranged between two adjacent first Laue-crystals 18a/20a, 20a/22a for deflecting a beam transmitted undiffracted by the previous first Laue-crystals 18a, 20a in the series is arranged to also deflect the beam that is Laue-diffracted by the previous first Laue-crystal 18a, 20a. This way, it is avoided that a beam that has been Laue-diffracted at one of the first Laue-crystals 18a, 20a is diffracted at another first Laue-crystal 20a, 22a in the monochromator 30 again. Likewise, the geometry of the monochromator 30 ensures that a beam that has been Laue-diffracted at one of the second Laue-crystals 18b, 20b is deflected once before passing another second Laue-crystal 20b, 22b, thereby avoiding a further Laue-diffraction at a second Laue-crystal.

[0055] Note that in the monochromator 30 of Fig. 6, the tilt angle between the first Laue-crystals 18a, 20a, 22a and the second Laue-crystals 18b, 20b, 22b does not correspond to twice the Bragg-angle, since the angular shift of the refractive deflection means 24 needs to be taken into account.

[0056] Further, note that the beams that are Laue-diffracted at the plural second Laue-crystals 18b, 20b, 22b diverge when leaving the monochromator 30, since they have passed different numbers of refractive deflection means 24. However, these individual beams extracted from the monochromator 30 can be focused to a single spot using an appropriate lens system.

[0057] In Fig. 7, yet a further monochromator 36 is shown, which has the currently most preferred geometry. The monochromator 36 also comprises two units 32, 34, where the first unit 32 contains three first Laue-crystals 18a, 20a, 22a and the second unit 34 contains three second Laue-crystals 18b, 20b, 22b. Note that in the monochromator 36, the first and second units 32, 34 are arranged in series, while in the monochromator 30 of Fig. 6, they were arranged in an interleaved relationship. That is to say, in the monochromator 36 of Fig. 7, all first Laue-crystals 18a, 20a, 22a are arranged in a series and all second Laue-crystals 18b, 20b, 22b are arranged in a further series that is arranged downstream of the series of first Laue-crystals 18a, 20a, 22a with regard to the propagation direction of the beam. Also, from a functional point of view, the order of the second crystals 18b, 20b, 22b in the second unit 34 is reversed in the sense that the most upstream first Laue-crystal 18a of the first unit 32 forms a Laue-crystal pair with the most downstream second crystal 18b of the second unit 34 and so on.

[0058] Refractive deflection means 24 are placed between each two neighbouring first Laue-crystals 18a, 20a, 22a of the first unit 32, in order to provide for the desired angular shift. Further refractive deflection means 38 are placed between each two neighbouring second Laue-crystals 18b, 20b, 22b of the second unit 34. Herein, the further refractive deflection means 38 compensate the effects of the refractive deflection means 24 arranged in the first unit 32. For example, the refractive deflection means 24 and 38 could be identical wedge arrays similar to those shown in Fig. 9 but with reversed orientation, as is symbolically shown in Fig. 7.

[0059] However, it is not necessary that all the refractive deflection means 24, 38 in the gaps between adjacent Laue-crystals are identical. Instead, it is sufficient that the reflection means 38 in the n^{th} gap between neighbouring second Laue-crystals 18b, 20b, 22b when counted in opposite propagation direction of the beam is adapted to compensate for the deflection provided by the deflection means 24 in the n^{th} gap between neighbouring first Laue-crystals 18a, 20a, 22a when counted in propagation direction of the beam.

[0060] Note that with the geometry of Fig. 7, generally all undiffracted transmitted or diffracted beams may pass through all Laue-crystals 18a/b, 20a/b, 22a/b of both units 32, 34 and all refractive deflection means 24, 38, while still ensuring that each beam portion of the desired energy is only Laue-diffracted by exactly one pair of the first and second Laue-crystals 18a/b, 20a/b, 22a/b.

[0061] The efficiency of each of the monochromators 16, 30 and 36 is further increased if the inherently diverging beam is made less diverging or even parallelized prior to entering the monochromator 16, 30, 36. For this, the collimation lenses, lens stacks or lens arrays discussed below with reference to Figs. 10, 11 can be ideally used. Note in this regard that a focusing lens acts as a collimation lens if the source of the diverging beam is placed in the focal point of the lens.

[0062] In Fig. 8, a schematic perspective view of a Laue-crystal unit 40 is shown, that could be used as one of the units 32 or 34 of Fig. 7. The unit shows three Laue-crystals 18, 20, 22 which are made from one ingot. Further shown are the refractive deflection means 24, which are formed by wedge arrays 24 in the present example. Note that Fig. 8 is also highly schematic and not drawn to scale. Further, the wedge arrays 24 can be adjusted with respect to each other by means of a flexure cut 42 and a piezo actuator 44. By controlling the piezo actuator 44, the relative orientation of the wedge arrays 24 can therefore be adjusted such as to tune the monochromator 36.

[0063] In Fig. 9(a) a plan view and in Fig. 9(b) a perspective view of an array 46 of triangular prisms 48 is shown which may be used as the aforementioned refractive deflection means 24, 38. The triangular prisms 48 have an isosceles triangle shape, wherein the height (h) of the triangle shape is smaller than 200 μm, preferably even smaller than 100 μm and more preferably even smaller than 50 μm, as miniaturizing allows for increasing the number of prisms 48 to accommodate in the array and hence for increasing the total refractory power. The prisms 48 are also referred to as "wedges" or "microwedges" in the following.

[0064] The wedge array 46 of Fig. 9 is etched from a semiconductor wafer, in particular Si and/or Ge. Accordingly, the thickness of the wedges of Fig. 9 corresponds to the thickness of the wafer, which is typically between 20 μm and 200 μm. A plurality of identical wedge arrays 46 can be stacked on top of each other, to thereby produce a thicker wedge array 46 having a thickness of several millimetres or even beyond a centimeter.

[0065] The wedge array 46 of Fig. 9 is comprised of a number M of series arrangements 50a, 50b, 50c of wedges 48 that are arranged in parallel, where the number M can again be chosen as desired. Further, each series arrangement 50a, 50b, 50c of wedges 48 contains a number N of wedges 48 arranged in series such as to be consecutively passed by a beam. Herein, the number N will depend on the total deflection angle that is intended. From a manufacturing point of view, hundreds of or even a thousand wedges 48 can be easily provided in each arrangement of prisms 50a, 50b, 50c.

[0066] In Fig. 10, a cross section (Fig. 10(a)) and a perspective view (Fig. 10(b)) of a 2-D focusing γ-lens 52 according to an embodiment of the invention is shown. The γ-lens 52 is "two-dimensional" in the sense that it is optically active in two dimensions, meaning that the lens surfaces 54, 56 are curved in two orthogonal sections A-A (shown in Fig. 10(a) and B-B (not shown). This means that a γ-beam will be focused in two dimensions, such as to converge to a focal "point". This is to distinguish the lens from 1-D-lenses described below, where the beam is only shaped in one dimension but left unaffected in another dimension such as to, for example focus a circular beam onto a line rather than onto a point.

[0067] The lens 52 is made from a nickel foil that is squeezed between two profiled pistons to acquire the convex shape that is particularly apparent from Fig. 10(a). With this embossing technique, the lens 52 can be manufactured comparatively easily and cheaply and to a high precision of about 100 nm. The lens surfaces 54 and 56 of the lens 52 have a rotational ellipsoid shape that is characterized by an inscribed tangential radius at its apex 58. Preferably, the radius R at the apex 58 is smaller than 2000 μm, preferably smaller than 1000 μm and preferably between 5 μm and

500 μm. The smaller the radius of curvature (i.e. the larger the curvature), the smaller the focal length.

[0068] As is further seen in Fig. 10, the lens 52 has mounts 60 at two sides, which may have a length of about 10 mm. With these mounts, a plurality of lenses 52 can be stacked one behind the other in a lens holder (not shown), to thereby add up the focusing power of multiple lenses. In practice, several hundreds or even a thousand of lenses 52 can be manufactured and stacked one behind the other.

[0069] As is further seen in Fig. 10(b), a hole 62 for ventilation is provided in the body of the lenses 52, thereby preventing a deformation of the lenses 52 when the lens stack is evacuated.

[0070] In Fig. 11, a schematic plan view (Fig. 11(a)) and a schematic perspective view (Fig. 11(b)) of an array 64 of 1-D lenses 68 is shown. The lens array 64 is comprised of three series arrangements 66a, 66b, 66c of lenses 68 that are arranged in series for being consecutively passed by a γ-beam. In the embodiment shown, N = 6 lenses 68 are arranged in series in each of the series arrangements 66a, 66b, 66c, however, the number N may in practice be much larger, i.e. N ≥ 10, preferably N ≥ 100 and more preferably N ≥ 300, in order to increase the refractive power of the lens array 64.

[0071] As is further seen in Fig. 11, only M = 3 lens arrangements 66a, 66b, 66c are arranged in parallel in the lens array 64, but in practical applications, the number M could be much larger.

[0072] Each of the lenses 68 constituting the lens array 64 has two lens surfaces 70, 72 that have a convex shape in one dimension only. The convex shape can be seen in the plan view of Fig. 11(a), the shape having a tangential radius R at the apex of each lens surface 70, 72 of between 1 μm and 500 μm, preferably between 10 μ and 80 μm. This means that γ-beams 74 as shown in Fig. 11(a) will only be focused in the paper plane of Fig. 11(a), but not within a plane vertical to the paper plane of Fig. 11(a). Accordingly, when the lens array 64 of Fig. 11 is used alone, a γ-beam 74 would be focused onto a line rather than onto a focal point. However, in practice two lens arrays 64 could be arranged in series one after the other and rotated by 90° with respect to each other such as to achieve a focusing in two dimensions.

[0073] The use of lens surfaces 70, 72 that are convex only in one dimension is advantageous from a manufacturing point of view. The lens arrays 64 of Fig. 11 can be made from a wafer, such as an Si and/or Ge wafer by vertical etching, thereby leading to the vertical wall parts of the lens surfaces 70, 72. In particular, in producing the lens array 64, according to one embodiment first a mask is generated by electron beam lithography. Thereafter, the material between neighbouring lenses 68 is etched for example by ion beam deep etching. Preferably, the wafer thickness is between 20 μm and 100 μm and more preferably between 50 μm and 200 μm. With these thicknesses, precise vertical walls can still be etched.

[0074] Further, a plurality of identical lens arrays 64 as shown in Fig. 11 can be manufactured and then stacked one on top of the other to thereby increase the total thickness of the lens array 64. The wafers in the stack can be grown or fused together. This way, a total thickness of a lens array 64 of more than 5 mm or even more than 8 mm can be achieved.

[0075] The embodiments described above and the accompanying figures merely serve to illustrate the method according to the present invention, and should not be taken to indicate any limitation of the method. The scope of the patent is solely determined by the following claims.

Claims

1. A monochromator (16, 30, 36) for monochromatizing a beam of γ-photons, x-ray photons having an energy higher than 10 keV or neutrons of an energy below 1 eV,
said monochromator comprising a plurality of pairs of Laue-crystals (18a/b, 20a/b, 22a/b), each pair of Laue-crystals having

    - a first Laue-crystal (18a, 20a, 22a) for diffracting a portion of an incoming beam that meets the Bragg-condition and transmitting the remainder of the incoming beam without diffraction, and
    - a second Laue-crystal (18b, 20b, 22b) arranged with respect to the first Laue-crystal (18a, 20a, 22a) such as to allow for a further Laue diffraction of the beam portion that was Laue-diffracted at the first Laue-crystal (18a, 20a, 22a) of said pair of Laue-crystals (18a/b, 20a/b, 22a/b),

    wherein the first Laue-crystals (18a, 20a, 22a) of all pairs of Laue-crystals (18a/b, 20a/b, 22a/b) are parallel to each other and the second Laue-crystals (18b, 20b, 22b) of all pairs of Laue-crystals (18a/b, 20a/b, 22a/b) are parallel to each other, and wherein the first Laue-crystals (18a, 20a, 22a) of the pairs of Laue-crystals (18a/b, 20a/b, 22a/b) are arranged in series with refractive deflection means (24) arranged inbetween such that the part of the beam that is transmitted without diffraction by one of said first Laue-crystals (22a, 24a) is deflected prior to impinging on the next first Laue-crystal (24a, 26a) in said series.

2. The monochromator (16, 30, 36) of claim 1, wherein the refractive deflection means (24) arranged between consecutive first Laue-crystals (18a, 20a, 22a) in said series of first Laue-crystals are adapted to deflect the beam by

an angle α, with $5 < \alpha < 200$ nrad, preferably $10 < \alpha < 100$ nrad, and/or
wherein the number of pairs of Laue-crystals (18a/b, 20a/b, 22a/b) is at least 5, preferably at least 10 and more preferably at least 50, and/or
wherein the first and second Laue-crystals (18a/b, 20a/b, 22a/b) of each pair of Laue-crystals (18a/b, 20a/b, 22a/b) are either

- parallel to each other, or
- inclined with respect to each other such as to allow for an energy selection by two consecutive Laue-diffractions, in particular inclined by twice a Bragg-angle of the desired wavelength, or
- shiftable between the two configurations.

3. The monochromator (16, 30, 36) of claim 1 or 2, wherein all first Laue-crystals (18a, 20a, 22a) are part of one fixed first unit (32) and all second Laue-crystals (18b, 20b, 22b) are part of one fixed second unit (34), wherein the first and second units (32, 34) are preferably each made from a single crystal block, in particular an Si or Ge block, wherein both blocks are preferably taken from the same ingot.

4. The monochromator (16, 30, 36) of one of claims 1 to 3, wherein a collimating lens, lens stack or lens array is arranged upstream of the monochromator (16, 30, 36) such as to parallelize or at least reduce the divergence of the beam prior to entering the monochromator (16, 30, 36)36.

5. The monochromator (16, 30, 36) of one of claims 1 to 4, wherein a beam that has already been Laue-diffracted by a first (second) Laue-crystal of one pair is deflected using a refractive deflection means (24) prior to passing a first (second) Laue-crystal of another pair of Laue-crystals, and/or
wherein the refractive deflection means (24) arranged between two adjacent first Laue-crystals (18a, 20a, 22a) for deflecting a beam transmitted without diffraction by the previous first Laue-crystal (18a, 20a) in said series is arranged to also deflect the beam Laue-diffracted by said previous first Laue-crystal (18a, 20a).

6. The monochromator (30) of one of claims 1 to 5, wherein the first and second Laue-crystals (18a/b, 20a/b, 22a/b) are arranged in the monochromator (30) such that the first and second Laue-crystals of each pair are adjacent to each other, or
wherein the first and second Laue-crystals (18a/b, 20a/b, 22a/b) are arranged in the monochromator such that all first Laue-crystals (18a, 20a, 22a) are arranged in a series and all second Laue-crystals (18b, 20b, 22b) are arranged in a further series that is arranged downstream of the series of first Laue-crystals (18a, 20a, 22a),
wherein first refractive deflection means (24) are placed between each two neighbouring first Laue-crystals (18a, 20a, 22a) and second refractive deflection means (38) are placed between each two neighbouring second Laue-crystals (18b, 20b, 22b) with regard to the propagation direction of the beam,
wherein the second refractive deflection means (38) in the n^{th} gap between neighbouring second Laue-crystals (18b, 20b, 22b) when counted in opposite propagation direction of the beam is adapted to compensate for the deflection provided by the first refractive deflection means (24) in the n^{th} gap between neighbouring first Laue-crystals (18a, 20a, 22a) when counted in propagation direction of the beam.

7. The monochromator (16, 30, 36) of one of claims 1 to 6, wherein the refractive deflection means (24) comprise an array (46) of prisms (48),
said array (46) of prisms (48) comprising at least one series arrangement (50a, 50b, 50c) of prisms (48) allowing for being consecutively passed by a beam, and/or wherein in said series arrangement (50a, 50b, 50c) of prisms (48), preferably a number N of prisms are arranged in series, such as to be consecutively passed by a beam, wherein $N \geq 2$, preferably $N \geq 10$ and more preferably $N \geq 100$, and/or
wherein at least the majority of prisms (48) in said array (46) of prisms (48) has a wedge shape with a base surface having a triangular shape,
wherein the height (h) of the triangular shape is smaller than 200 μm, preferably smaller than 50 μm,
wherein the base surface preferably has an isosceles triangle shape,
wherein the angle γ between the two equal sides of said isosceles triangle is preferably between 5° and 120°, more preferably between 15° and 90°, and/or
wherein said array (46) of prisms (48) comprises a number M of series arrangements (50a, 50b, 50c) of prisms (48) arranged in parallel,
wherein $M \geq 2$, preferably $M \geq 4$ and more preferably $M \geq 10$.

8. The monochromator (16, 30, 36) of claim 7, wherein said array (46) of prisms (48) is at least in part made from one

or more wafers, in particular Si and/or Ge wafers, in which the prisms (48) are formed by etching,
wherein said one or more wafers preferably has/have a thickness between 20 μm and 200 μm, preferably between 50 μm and 100 μm, and/or
wherein said array (46) of prisms (48) is at least in part made from a stack of a plurality of identically etched wafers, wherein said wafers of said stack are preferably grown or fused together, and/or
wherein the total thickness of the stack of wafers is preferably 5 mm or more, more preferably 8 mm or more.

9. The monochromator (16, 30, 36) of one of claims 1 to 8, said monochromator being adapted to generate a beam of γ-photons having an energy for which the energy dependent index of refraction of the material of the refractive deflection means (24) has a real part that is larger than 1, and in particular for a beam of γ-photons having an energy that is larger than 100 keV, preferably larger than 300 keV, more preferably larger than 500 keV, larger than 700 keV and larger than 1 MeV.

10. The monochromator (16, 30, 36) of claim 4 and 9,
wherein said collimating lens (52) is a convex lens having at least one, preferably two lens surfaces (54, 56) having a convex shape in two dimensions, and in particular, a rotation-ellipsoid shape,
wherein the tangential radius R at the apex of the lens is < 2000 μm, preferably < 1000 μm and preferably between 5 μm and 500 μm, and/or
wherein the collimating lens (52)is made from an embossed foil, in particular a foil comprising one of Be, Al, Ni, Ta or Th as its main constituents.

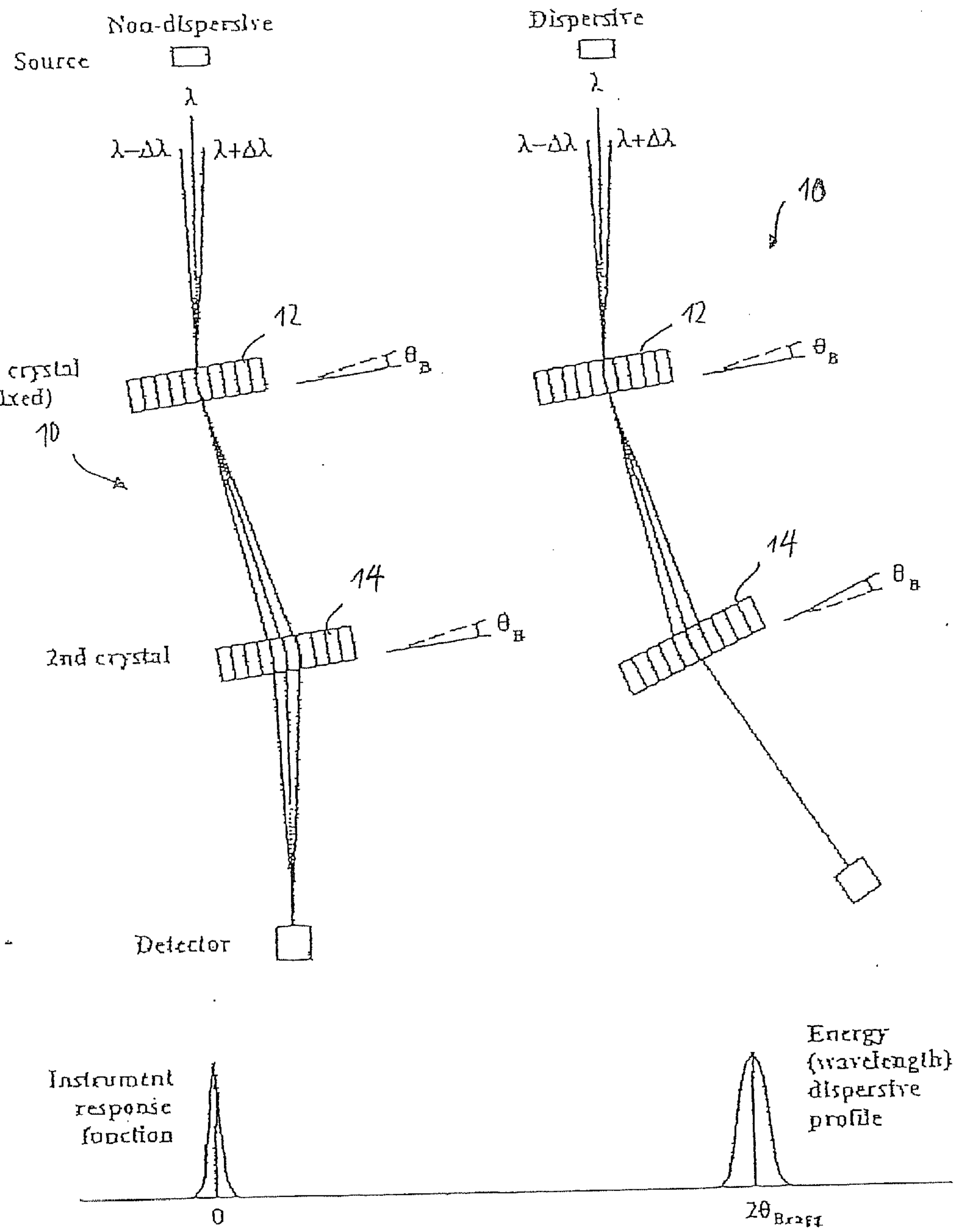
11. The monochromator (16, 30, 36) of claim 4 and 9, wherein said lens stack is a stack of N collimating lenses (52) as defined in claim 10 arranged in series, in particular stacked one behind the other in a lens holder, wherein N is between 2 and 10000, preferably between 10 and 200.

12. The monochromator (16, 30, 36) of claims 4 and 9, whereinsaid lens array (64) comprises at least one series arrangement (66a, 66b, 66c) of lenses (68) allowing for being consecutively passed by a γ-beam, wherein at least the majority of the lenses (68) has at least one, preferably two lens surfaces (70, 72) having a convex shape in at least one dimension.

13. The monochromator (16, 30, 36) of claim 12, wherein the mean radius of curvature of the convex shape or the tangential radius at the apex of the convex shape is between 1 μm and 500 μm, preferably between 10 μm and 80 μm, and/or
wherein in said series arrangement (66a, 66b, 66c), a number N of lenses are arranged in series such as to be consecutively passed by a γ-beam, wherein $N \geq 10$, preferably $N \geq 100$, and more preferably $N \geq 300$, and/or
wherein said lens array (64) comprises a number M of series arrangements (66a, 66b, 66c) of lenses (68) arranged in parallel,
wherein $M \geq 2$, preferably $M \geq 4$, and more preferably $M \geq 10$.

14. The monochromator (16, 30, 36) of claim 12 or 13, wherein said lens array (64) is at least in part made from one or more wafers, in particular Si- and/or Ge-wafers, in which the lens surfaces are formed by etching,
wherein said one or more wafers preferably has/have a thickness between 20 μm and 200 μm, preferably between 50 μm and 100 μm, and/or
wherein said lens array is at least in part made from a stack of a plurality of identically etched wafers,
wherein said wafers of said stack are preferably grown or fused together and/or wherein the total thickness of the stack of wafers is preferably 5 mm or more, more preferably 8 mm or more.

15. The monochromator (16, 30, 36) of one of claims 12 to 14, comprising a combination of two lens arrays (64) arranged in series, wherein the arrays (64) are oriented with respect to each other, such that each of the two lens arrays (64) focuses or collimates a γ-beam within a different plane, wherein said planes are preferably arranged at 90° with respect to each other.


Non-dispersive
Source
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12
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2nd crystal
Detector
Dispersive
λ
λ−Δλ
λ+Δλ
10
12
θ
14
θ
Instrument
response
function
0
Energy
(wavelength)
dispersive
profile
2θ

Fig. 1

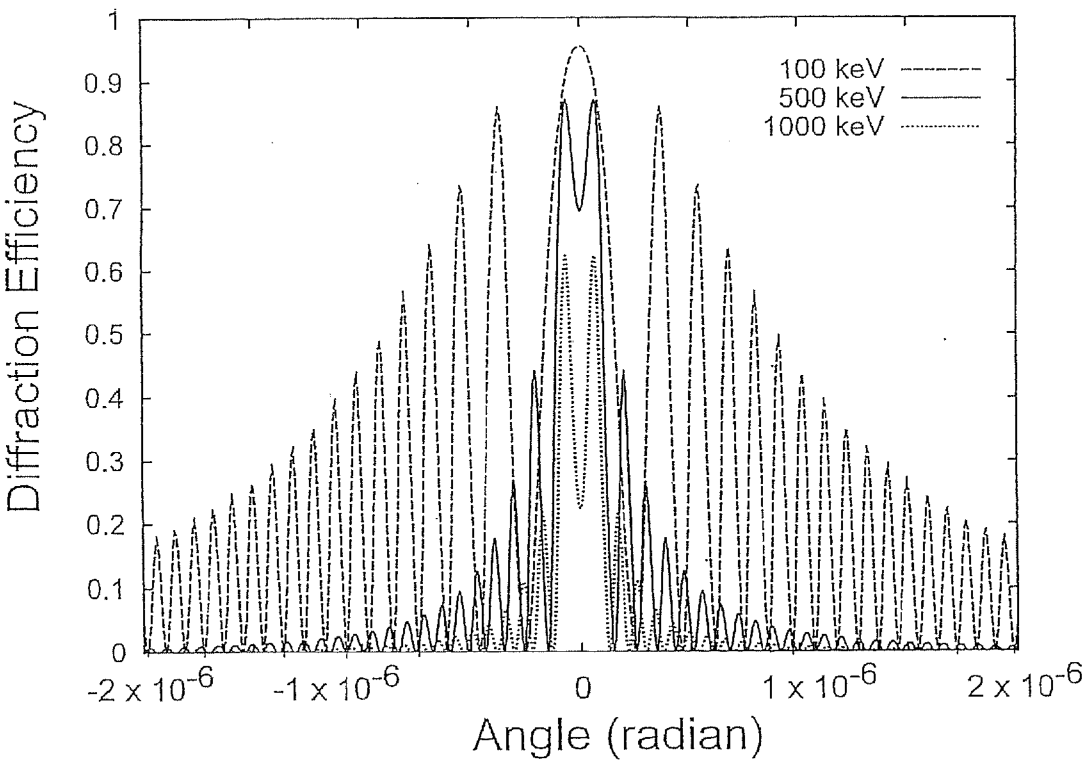
Diffraction Efficiency
Angle (radian)
100 keV
500 keV
1000 keV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-2 x 10^-6
-1 x 10^-6
0
1 x 10^-6
2 x 10^-6

Fig. 2

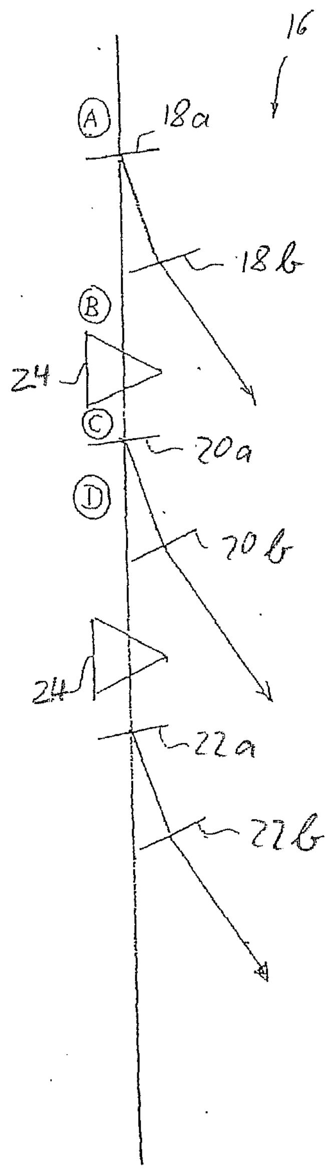
16
A
18a
18b
B
24
C
20a
D
20b
24
22a
22b

Fig. 3

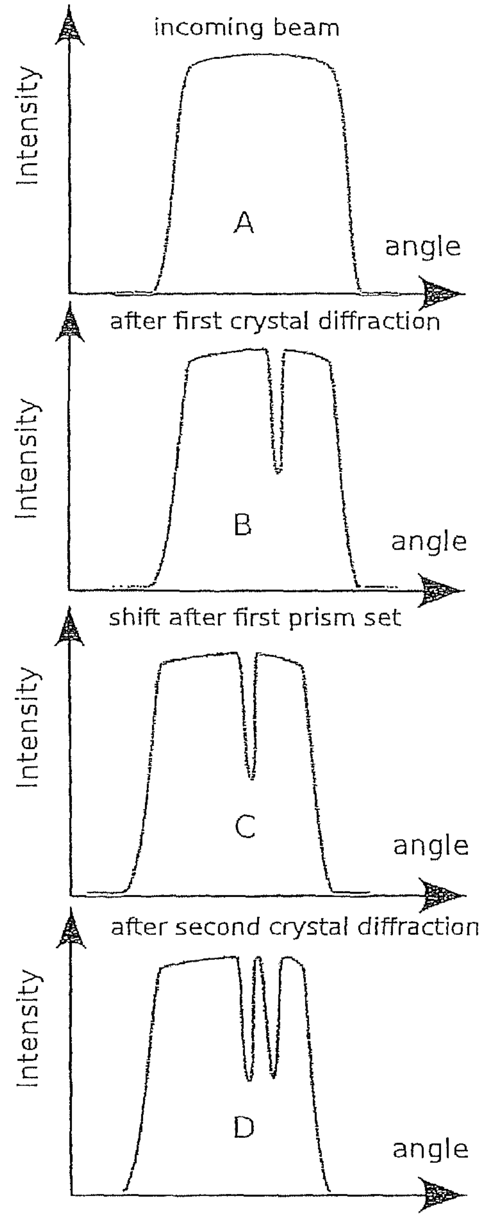
incoming beam
Intensity
A
angle
after first crystal diffraction
Intensity
B
angle
shift after first prism set
Intensity
C
angle
after second crystal diffraction
Intensity
D
angle

Fig. 4

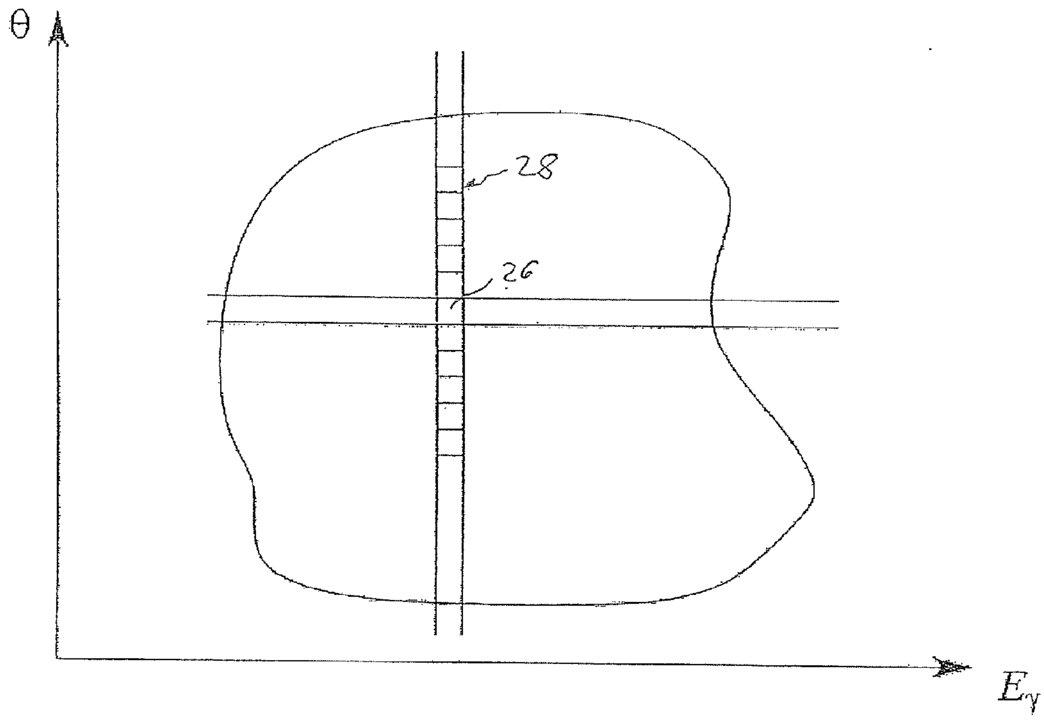

Fig. 5

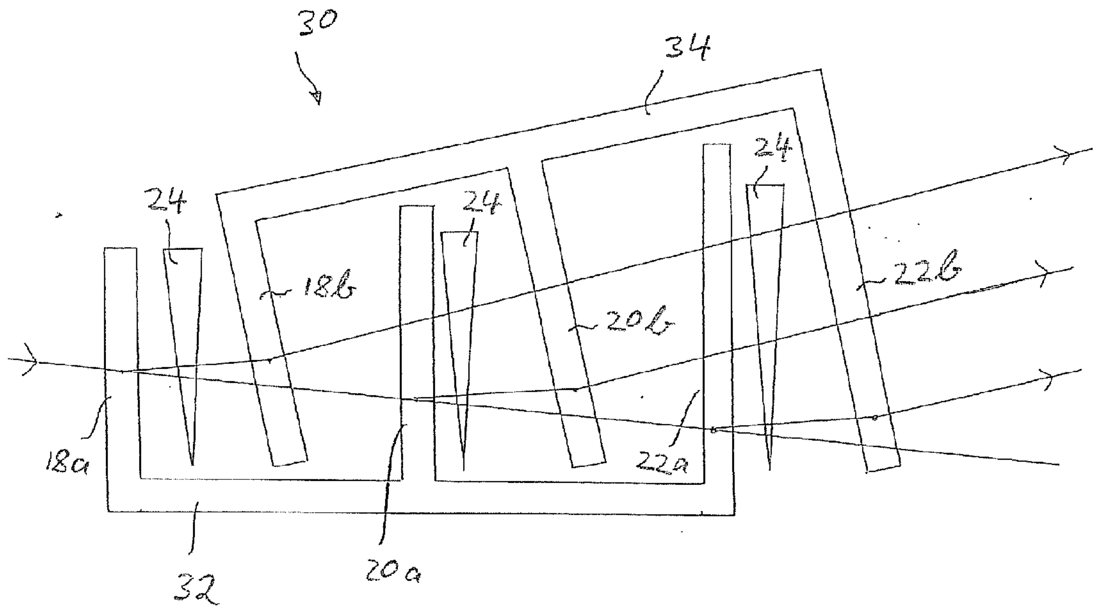

Fig. 6

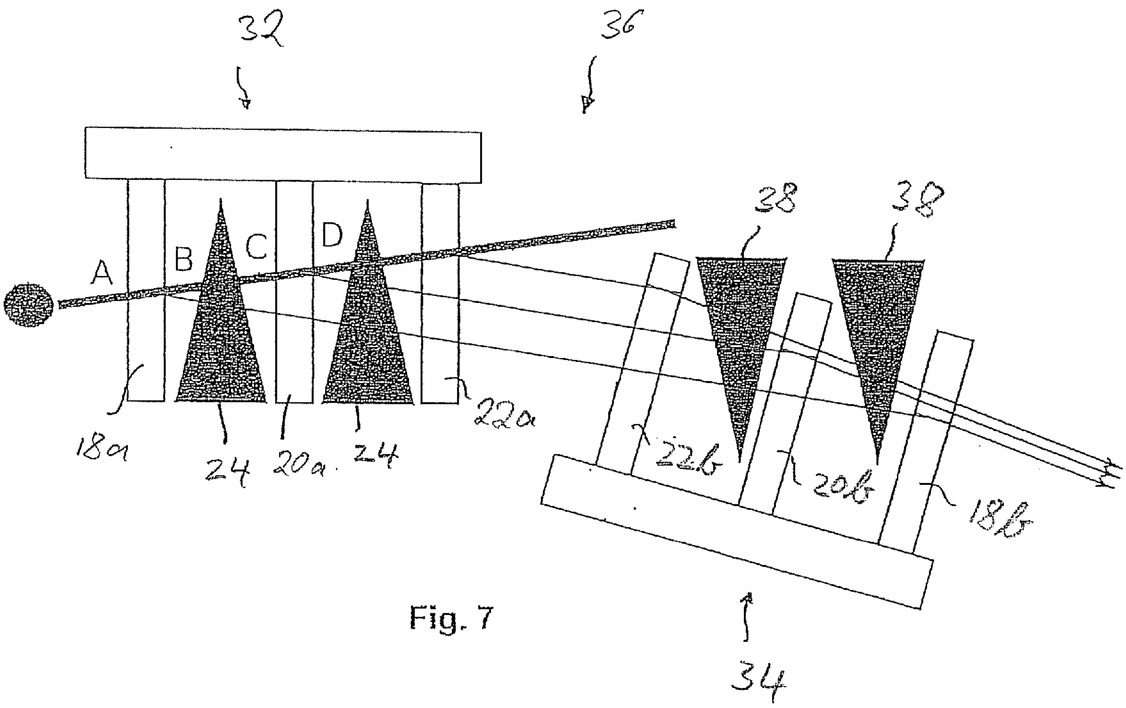
32
36
A
B
C
D
38
38
18a
24
20a
24
22a
22b
20b
18b
34

Fig. 7

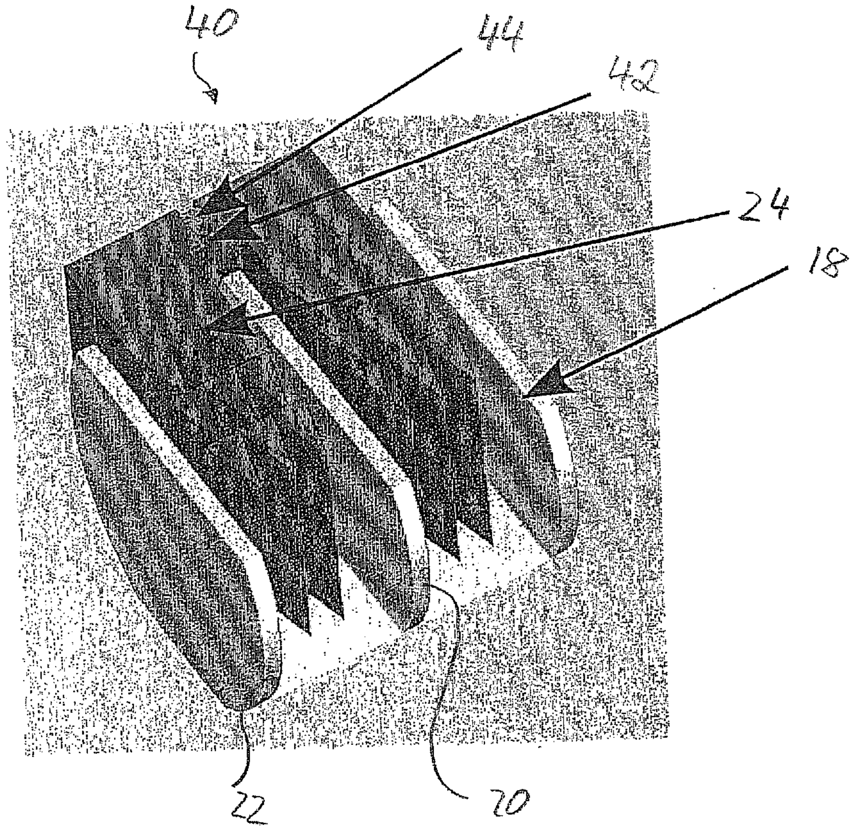
40
44
42
24
18
22
20

Fig. 8

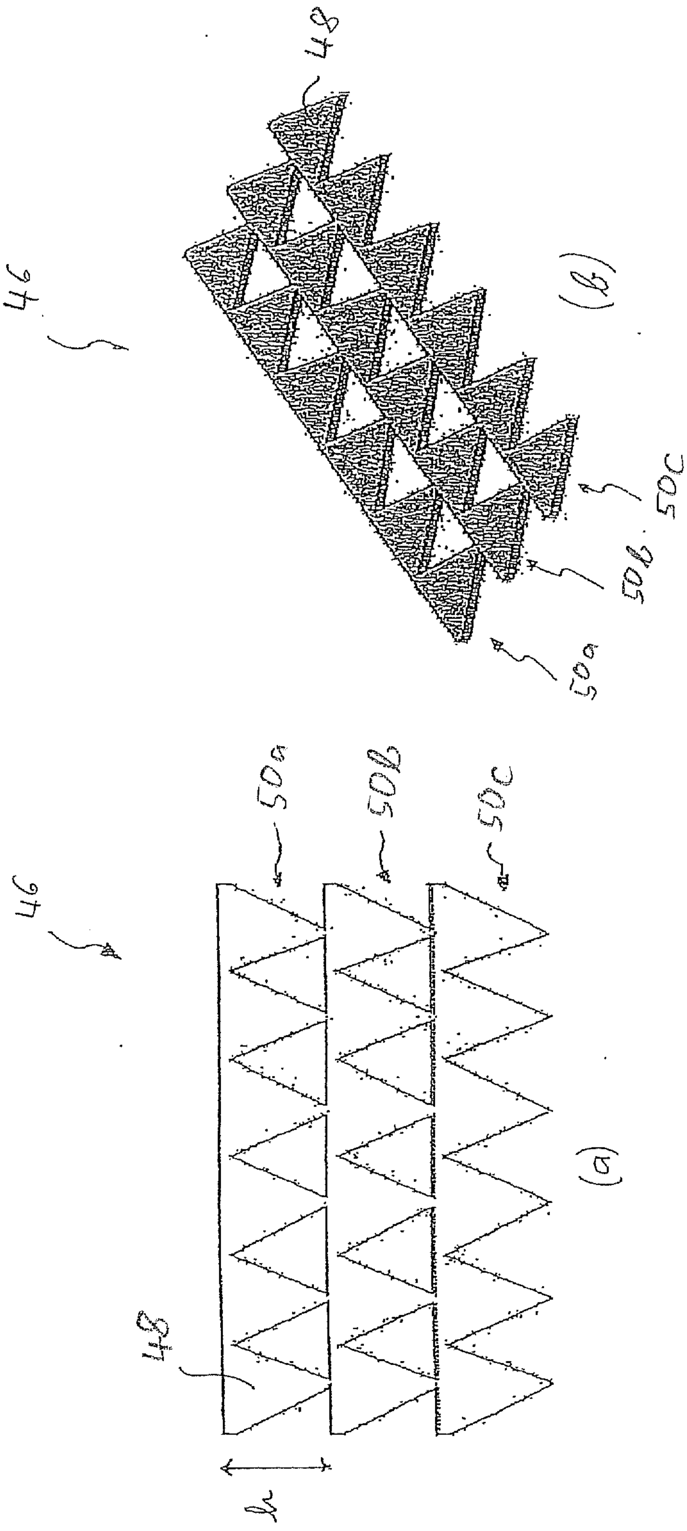

Fig. 9

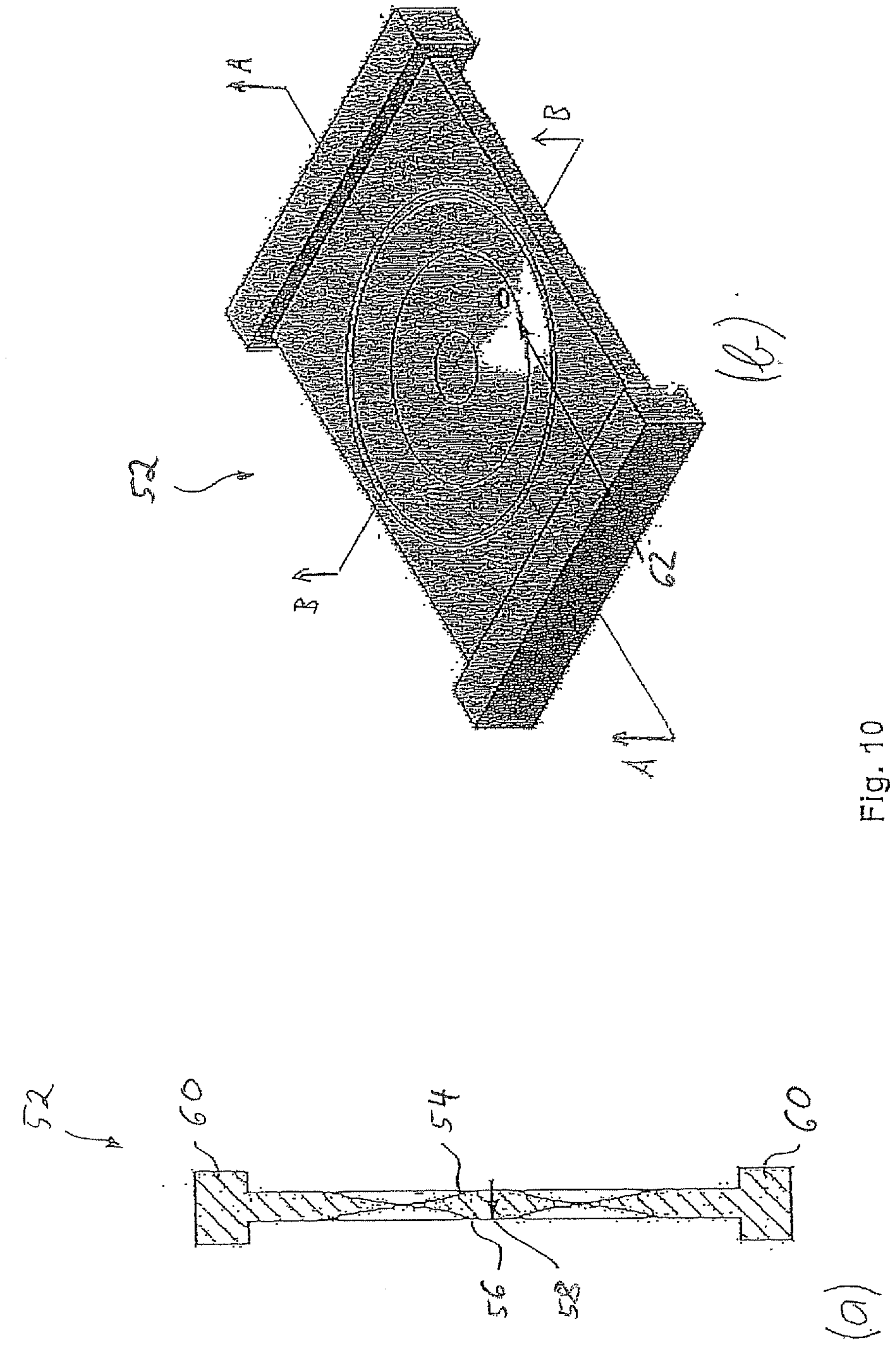

Fig. 10

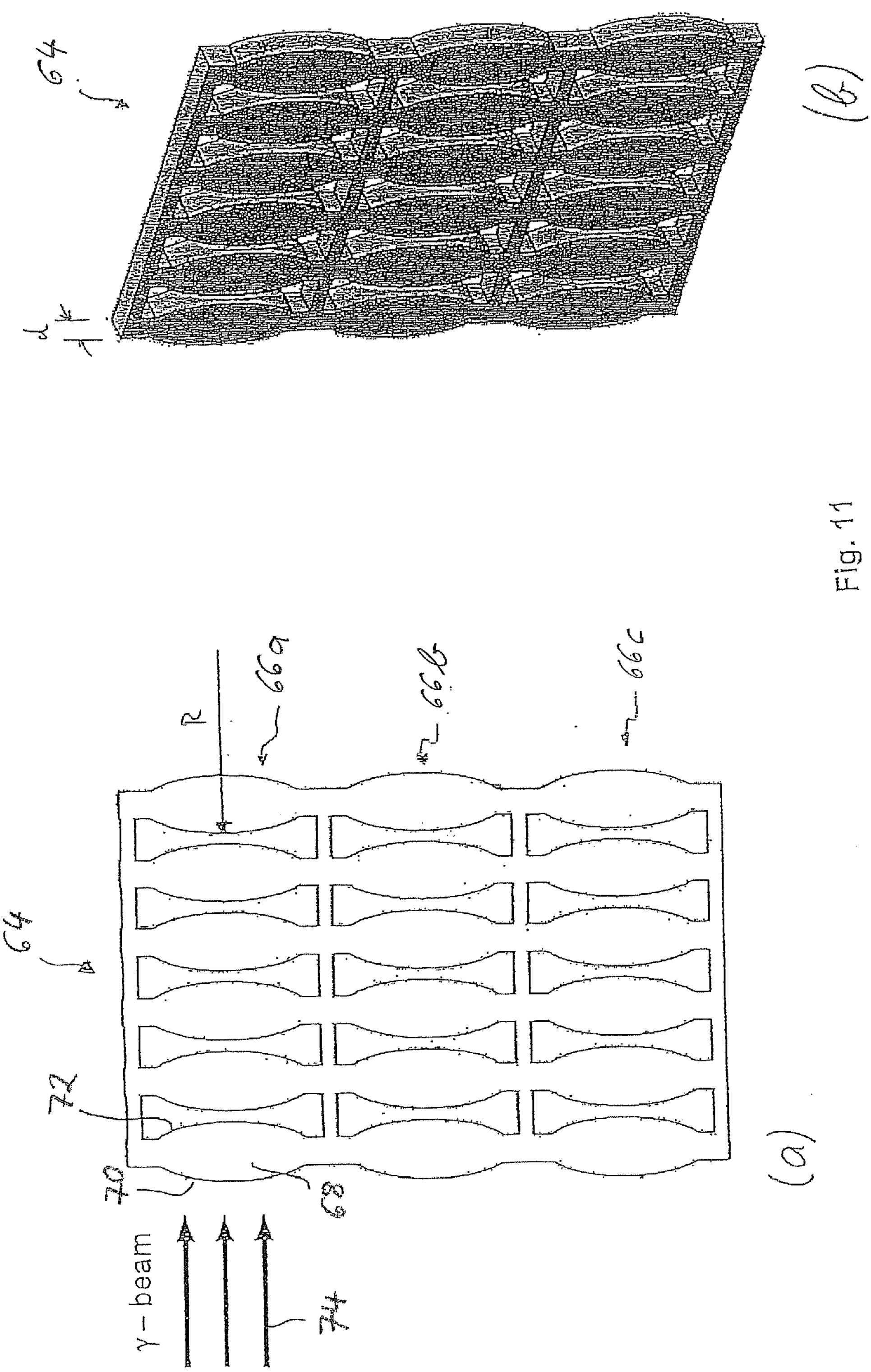

Fig. 11

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EUROPEAN SEARCH REPORT

Application Number
EP 11 19 5252

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	DD 133 487 A1 (BOTHE HANS KARL; KOERNER GUENTHER) 3 January 1979 (1979-01-03) * page 1, lines 1-6 * * page 3, lines 5-27 *	1-15	INV. G21K1/06
A	ALLMAN B E ET AL: "Neutron interferometry instrumentation at MURR", NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A: ACCELERATORS, SPECTROMETERS, DETECTORS, AND ASSOCIATED EQUIPMENT, ELSEVIER BV * NORTH-HOLLAND, NETHERLANDS, vol. 412, no. 2-3, 1 August 1998 (1998-08-01), pages 392-419, XP004134043, ISSN: 0168-9002, DOI: 10.1016/S0168-9002(98)00479-3 * paragraphs 2, 4.1, 4.6; figures 3,15,23 *	1-15	
A	TAKEYAMA A ET AL: "Computed tomography for reconstructing refractive index distribution using an X-ray shearing interferometer", SICE. PROCEEDINGS OF THE SICE ANNUAL CONFERENCE. INTERNATIONALSESSION PAPERS, TOKYO, JP, vol. 4, 7 August 2002 (2002-08-07), pages 2524-2526, XP008096633, * the whole document *	1-15	TECHNICAL FIELDS SEARCHED (IPC) G21K
A	US 2008/019482 A1 (YONEYAMA AKIO [JP] ET AL) 24 January 2008 (2008-01-24) * paragraphs [0010], [0017], [0020], [0023], [0025], [0044], [0054], [0085], [0086], [0089]; figure 12 *	1-15	

-/--

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	17 January 2013	Giovanardi, Chiara

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EUROPEAN SEARCH REPORT

Application Number
EP 11 19 5252

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
T	D. HABS ET AL: "Refractive Index of Silicon at [gamma] Ray Energies", PHYSICAL REVIEW LETTERS, vol. 108, no. 18, 1 May 2012 (2012-05-01), XP055038119, ISSN: 0031-9007, DOI: 10.1103/PhysRevLett.108.184802 -----		

TECHNICAL FIELDS SEARCHED (IPC)

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
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17-01-2013

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DD 133487 A1	03-01-1979	NONE	
US 2008019482 A1	24-01-2008	JP 5041750 B2	03-10-2012
		JP 2008026098 A	07-02-2008
		US 2008019482 A1	24-01-2008

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Patent documents cited in the description

- EP 11188251 A **[0022]**

Non-patent literature cited in the description

- **E.G. KESSLER et al.** *Nucl Inst. Meth. A,* 2001, vol. 457, 187 **[0005]**
- **J.S. TOLL.** The Dispersion Relation for Light and the Applications involving Electron Pairs. Princeton University, 1952 **[0023]**