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References cited:
FR-A- 2 665 955
US-A- 5 864 381

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Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention is directed to increasing spatial resolution of Hartmann type wavefront sensors, more particularly to using a hard aperture to limit the wavefront area being sensed.

Description of Related Art

[0002] The use of lens arrays in Hartmann wavefront sensors generally is disclosed in U.S. Patent No. 5,233,174 and French Patent No. 2 665 955. Hartmann wavefront sensing began as a technique for optical metrology, but the adoption of the technique by the adaptive optics community changed its primary usage. The adaptive optics community developed high photon efficiency high-speed sensors. Recently Hartmann sensors have been developed to address the needs of optical metrology again. Today most optical metrology is done with interferometry because of the availability of commercial systems and the coupled high dynamic range and high resolution, but improvements to the Hartmann sensor allow it to compete with interferometry for the optical metrology market. Shack-Hartmann wavefront sensor systems are being sold today for approximately one quarter the cost of commercial interferometers. These Shack-Hartmann wavefront sensors have sensitivity comparable to commercial interferometers and offer vibration insensitivity and typically higher dynamic range in a single compact package.

[0003] One major drawback of the Shack-Hartmann wavefront sensor is the inherently limited resolution due to the size of the lenses in the lens array. To see features smaller than a lens diameter, the wavefront had to be magnified before entering the sensor with a lens or set of lenses. The disadvantage of this technique is that the magnifying lenses then impose their own aberrations and the field of view of the wavefront sensor is reduced. Magnification of the wavefront reduces the sensor’s field of view but allows for higher resolution at the cost of the dynamic range.

[0004] There are a number of metrology applications where both the spatial resolution and the sensitivity of the measurement are extremely critical. As an example, consider the application of silicon wafer metrology, for example as set forth in commonly assigned, co-pending Application Serial No. 09/340,502 entitled “Apparatus and Method for Evaluating a Target Larger than a Measuring Aperture of a Sensor” filed July 1, 1999, the entire contents of which are hereby incorporated by reference for all purposes. That application is directed to measuring an object that is larger than the sensor aperture. When the goal is to examine extremely small dimples or defects, e.g., 5nm, having a small spatial extent, e.g., 1-2 mm, on the surface of a silicon wafer requires a wavefront sensor with sufficient resolution to measure the height, resulting in fairly long focal length lens arrays. However, long focal length lens arrays are also required to be fairly large in diameter. In other words, the diameter or aperture of the sensor needed to detect the extremely small height of the feature is now larger than the spatial extent of the feature, making the feature irresolvable by the sensor. Thus, while a sensitive enough sensor can be made, the spatial resolution has been compromised.

SUMMARY OF THE PRESENT INVENTION

[0005] The present invention is therefore directed to a wavefront sensor that substantially overcomes one or more of the problems due to the limitations and disadvantages of the related art.

[0006] It is an object of the present invention to create a sensor having both high spatial resolution and good height sensitivity. This combination high spatial resolution and good sensitivity may also enable a variety of other applications such as flat panel display measurement, roll and sheet glass, plastic or metal film measurement, and a variety of other uses.

[0007] More particularly, it is an object of the present invention to extract sub-lens features from the wavefront sensor, referred to herein as knife-edge wavefront sensing. The basic idea is to move the wavefront across the lens array in steps that are a fraction of a lens diameter. The hard edges of the lens aperture, like a knife-edge, adjust the section of the wavefront exposed to each lens. The tilt seen by each lens can be determined using centroiding for each of the different positions of the wavefront and the features of the wavefront smaller than a lens can be determined. Thus, in accordance with the present invention, the spatial resolution of the sensor is increased by using the hard aperture of the lens to limit the wavefront being sensed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The foregoing and other objects, aspects and advantages will be described with reference to the drawings, in which:

Figures 1A-1C illustrate different tilted apertures for knife-edge wavefront sensing;
Figure 2 show the Fourier modeling results for knife-edge wavefront sensing for a wavelength of 633 nm;
Figure 3 is a schematic illustration of a system for testing knife-edge wavefront sensing;
Figure 4 is a plot from the scanning of a diffraction grating using knife-edge wavefront sensing;
Figure 5 is a plot of the signal recorded by an array of lenses as a pair of 600-micron diameter lenses separated by 160 microns was translated across
the lens array in ten-micron steps; and

Figure 5 is a schematic diagram of knife-edge wavefront sensing in a metrology application.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0009] Each lens in a Shack-Hartmann wavefront sensor measures the tilt seen by that lens by determining the position of the spot at the focus of the lens, typically with a centroid algorithm. This procedure works well if there is an average tilt to the wavefront over the lens.

[0010] If the wavefront has features smaller than the lens, they cannot be seen with the Hartmann sensor. However, by moving the sensor relative to the test object by a fraction of a lens, the limits over which the average tilt is performed are changed. The small section of the wavefront being viewed after the sensor moves will be dubbed the new region and the section no longer seen by a given lens will be called the old region. This motion of the sensor will result in a shift in the centroid if there is a difference in tilt between the new region and the old region. This allows for wavefront features to be viewed if they are on the order of the sensor displacement and produce a wavefront tilt shift because of the motion.

[0011] In one embodiment, the aperture of the lens itself, such as shown in Figure 1A, may be used to limit the wavefront being viewed. As the lens is translated relative to the wavefront reflected from the test object, the aperture of the lenslet measures a different portion of the wavefront. Since each lenslet measures the average slope over its aperture, variations in this difference lead to a measurement of the wavefront at higher resolution than the lenslet array. For isolated or non-regular features on the test object, these moving averages may be integrated to provide a detailed, high-resolution map of the surface. It is only necessary to scan one lenslet diameter in each direction (x and y), since the lenslet array provides multiple sampling at its own resolution. The net result is a series of images of focal spot patterns that may be analyzed to produce the wavefront. The sequence allows the lenslet resolution measurements to be filled in with the intervening values. Note that the measurements produce wavefront slope information, which may be integrated to produce the wavefront using any number of different wavefront reconstructors. Thus, by moving the wavefront sensor some non-integral number of lenslet will allow resolution of features that are smaller than the aperture of the lenslets.

[0012] Typically, such non-integral movement alone, using the lenslets themselves as hard apertures, is sufficient to resolve sub-aperture features. However, there are some wavefronts that will not produce a change in the average tilt when using the lenslets as hard apertures even when moved by non-integral steps. For example, a wavefront consisting of an integer number of sinusoidal periods, e.g., from a diffraction grating, will not produce such a change, since the average tilt induced by this aberration is zero for an averaging window of this size no matter where the start or stop of the averaging is located. Because of this, a break in the spatial frequency of the lenses has to be created. Tilting one or two of the edges of the square aperture of typical Shack-Hartmann lenses, as shown in Figures 1B and 1C, respectively, accomplishes this. This tilting may take numerous forms, for example, may also result in a diamond shaped aperture. The important feature of the tilt is to break the spatial frequency of the square aperture and the selection of the aperture shape will depend on ease of manufacture. This aperture may be realized by providing a blocking aperture to the square lenslet array or by creating an array of lenslets having the desired aperture shape.

[0013] Applying linear optics theory, the efficacy and transfer function of using tilt to resolve sub-aperture features for a highly periodic structure can be determined. Assume that the wavefront shaped by a perfect two-order blazed grating such that the angle of diffraction can be given by Equation (1),

$$\sin \theta = \lambda / \Lambda$$

where $\lambda$ is the wavelength of light and $\Lambda$ is the grating period. The separation of the spots after the lens would be given by Equation (2),

$$\Delta x = f \sin \theta$$

where $f$ is the lens focal length. If the lens aperture is designed perfectly for the wavefront, the number of grating periods distributed over the lens aperture is an integer plus one half. The amount of light in each order can be approximated by the amount of light covering the piece of the blazed grating diffracting it in each direction. Thus, the intensity in each order is given by Equation (3),

$$I_x = \frac{d \cdot \Lambda / 2}{2 \Lambda}$$

$$I_y = \frac{d \cdot \Lambda / 2}{2 \Lambda} + 1$$

where $d$ is the diameter of the lens and $\Lambda$ is the grating period.

[0014] Applying this to the centroid or first moment formula, the center of this intensity pattern is given by Equation (4),

$$\bar{x} = \frac{\sum f(x,y) \cdot x}{\sum f(x,y)} = \frac{(I_x - I_y) \cdot \Delta x}{(I_x - I_y)}$$

Using the paraxial ray approximation ($\sin \theta = \tan \theta = \theta$)
and assuming that $\lambda$ is much greater than $d$, the simplification of Equation (4) leaves Equation (5),
\[
\frac{x}{f} = \frac{\rho}{d}
\]
where $f$ is the focal length, $\lambda$ is the wavelength, and $d$ is the diameter. This formula is also commonly known as the spot size of a square lens. The shift in the centroid is actually double this number because as the lens is scanned, the light will oscillate between the two orders. Therefore, the shift in the centroid is exactly the spot diameter of a square lens.

[0015] One practical limit of this technique is when the diffracted light diffraets out from behind the lens into the adjacent lens in the array. To determine the maximum grating period, the diffraction angle of light from a grating defined above is set equal to the maximum measurable tilt angle, given by Equation (6)
\[
\theta = \tan^{-1}\left(\frac{d - \left(\frac{\lambda f}{d}\right)}{2f}\right)
\]
Assuming that the spot size is small compared to the lens diameter and using the paraxial ray approximation, the maximum grating period is found to be approximately Equation (7),
\[
\Lambda_{\text{max}} = \frac{2\rho}{d}
\]
which is equal to the square lens spot diameter. To push the limit of the resolvable grating period, some of the lenses could be masked out to create a lower lens density, but higher grating period resolution.

[0016] Thus, using the approximations presented above, the centroid motion and the minimum resolvable grating period will be equal to the spot diameter. To verify this, Fourier transform modeling was performed on a variety of lenses and a variety of apertures with respect to spatial wavelength. The focal plane of a lens with a known hard aperture was modeled while moving the wavefront in the x direction in steps of one tenth of a period. The centroid was performed after pixelating the intensity to a thirty-by-thirty pixel array and digitizing to eight bits. Then the maximum centroid shift was determined as the wavefront was moved.

[0017] Figure 2 shows a result of this modeling with the centroid response plotted against the spatial frequency of the sinusoidal grating. The square aperture lens, as shown in Figure 1A, shows the expected spatial frequency resonances, while the lenses with single tilted side or the lenses with double tilted side break the spatial frequency enough to flatten out the peak-to-valley centroid shift. The spot diameter of this square lens for 633nm light is about 4.1 microns. This appears to be approximately a factor of three higher than the value predicted by the linear optics theory. The discrepancy can be accounted for by the numerous approximations in the theory. The behavior is well predicted by the linear optics theory. Once the appropriate aperture tilt was applied, the response is effectively constant with respect to the spatial wavelength of the diffraction grating.

[0018] Microlenses arrays were fabricated using standard integrated circuit techniques, e.g., reflowing photosist, using binary masks or using gray scale masks. The microlenses may be shaped to create the desired apertures or the apertures may be physically applied to the microlenses, e.g., by doing a lift-off of 200nm of aluminum. When applied to circular microlenses, the apertures in all three embodiments were designed to be squares with sides equal to the diameter times the square root of two such that they fit inside the circular microlenses. Apertures were designed with no aperture tilt, aperture tilt on one side, and aperture tilt on both sides. The aperture tilt for each aperture was one-eighth the circular lens diameter.

[0019] Several different lens arrays were fabricated. The lens diameters were 150 microns, 200 microns, 250 microns, and 300 microns. The sag on all the lenses is approximately the same at 12.5 microns. The focal lengths were then calculated to be 0.49 mm, 0.87 mm, 1.36 mm and 1.96 mm respectively.

[0020] Two different test objects were measured using the knife-edge wavefront sensing technique: 600-micron diameter lenses and a 28-micron wavelength diffraction grating. Figure 3 is a schematic illustration of the experimental setup for these measurements. A light source 30, e.g., a HeNe laser, is expanded by a magnifying system 32 impinges on a test object 34 under measurement. A lens 36 re-images the test object onto the lens array 38. The focal plane of the lens array 38 was re-imaged onto a CCD 44 using a magnifying lens 42. An iris 46 was placed at the focus of the lens 36 to limit the spatial frequency impinging on the lens array and to avoid stray scattered light causing crosstalk. The test object was placed on a three-axis translation stage with motion parallel to the table and normal to the propagation controlled by a micrometer capable of one-micron accuracy.

[0021] All the measurements made were done with the 150-micron circular diameter lens array 38 that had apertures with two sides tilted thereon. The first test object 34 was a phase-only diffraction grating made using a single photolithographic step and transferred into the glass using a CF$_4$ and O$_2$ plasma etch. The spatial frequency of the binary grating was measured on a profilometer to be about 28 microns. Adjusting the width of iris 46 at the focus of the lens 36 blocked the diffraction beyond the first orders. The grating was then measured with the knife-edge wavefront sensing setup using one-micron steps. The change in the position of the centroid of the focal spots was measured using the CLAS-2D software provided by Wavefront Sciences, Inc. Figure 4
shows the centroid shift with respect to displacement for two separate lenses and the sinusoidal fits to this data. The sinusoidal fits extracted a spatial wavelength of 27 microns.

[0022] The next test object 34 measured with the knife-edge wavefront sensing technique was a pair of lenses 600 microns in diameter and 2 microns tall with about 160 microns between them. Figure 5 shows the displacement of the centroid of the focal spots of six lenses approximately centered on the lens pair as the pair was translated in 10-micron steps across the lens array. Since the wavefront sensor measures the derivative, the expected result of this measurement is a pair of linear changes in the centroid location with respect to displacement. The linear portions of the curve were fit and the results were slopes of -0.0544 and -0.058, and residual squared of 0.97 and 0.99 on the left and right respectively. The sharper features are caused by the edge effects in scanning a circular lens across an almost square aperture. Integration of these linear ramps will produce parabolic lens profiles that closely match the test object shape.

[0023] Use of the knife-edge wavefront sensing of the present invention for metrology applications is schematically illustrated in Figure 6. Here, light 60 from a light source is provided to a lens 62 that directs the light onto the test object 34. Light reflected from the test object 34 is incident on the lenslet array 38. This lenslet array is moved relative to the test object by a non-integral number of lenslets. The output of the lenslet array is provided to a detector in the same manner disclosed regarding Figure 3.

[0024] Thus, knife-edge wavefront sensing in accordance with the present invention allows Shack-Hartmann wavefront sensors to resolve features smaller than the size of an individual lens by moving the sensor in steps across the wavefront that are a non-integral number of apertures. Using linear optics theory, the fundamental limits of this technique have been shown to be the diffraction limit of light. This technique allows for more resolution for applications like optical metrology and laser beam characterization. To determine the surface profile of the test object, a reconstruction method would be applied as in conventional Hartmann wavefront sensing. In many applications, this technique will be particularly useful when combined with other techniques, e.g., the stitching application, to obtain information about an object that is larger than the aperture, but has features smaller than the aperture. The technique, while only demonstrated here in one dimension, is applicable to a two-dimensional scan as well. Further, while the non-integral steps used in the examples were all smaller than the aperture, non-integral steps that are larger than the aperture, e.g., 1.25 times the aperture size, may also be used.

[0025] While the present invention is described herein with reference to illustrative embodiments for particular applications, it should be understood that the present invention is not limited thereto. Those having ordinary skill in the art and access to the teachings provided herein will recognize additional modifications, applications, and embodiments within the scope thereof and additional fields in which the invention would be of significant utility without undue experimentation.

Claims

1. A method for improving spatial resolution of a Hartmann-type wavefront sensor (38, 42, 44) including a lens array (38), the method characterised by:

   a) providing a plurality of apertures (38) associated with the lenses of said lens array;
   b) providing a relative movement between the sensor (38, 42, 44) and a wavefront (34) to be sensed by a distance corresponding to a non-integral number of apertures; and
   c) determining features of the wavefront smaller than a lens of the lens array according to a shift in location of the focal spots between translations.

2. The method of claim 1, wherein said translating consists essentially of only moving the wavefront sensor (38, 42, 44).

3. The method of claim 1, wherein said translating consists essentially of only moving the wavefront (34).

4. The method of claim 1, wherein said translating comprises moving both the wavefront (38, 42, 44) and the wavefront sensor(34).

5. The method according to any one of the preceding claims, wherein the apertures are hard apertures.

6. The method according to any one of the preceding claims, wherein said providing comprises forming the plurality of apertures on a lenslet array (38) of the wavefront sensor.

7. The method of any one of claims 1 to 5, wherein said providing comprises forming a lenslet array (38) with each lenslet having a desired aperture.

8. A Hartmann-type wavefront sensor (38, 42, 44) comprising:

   a) a lens array (38); and
   b) a device (44) for sensing a position of a spot generated by the wavefront sensor (38, 42, 44), the sensor characterised by:
   c) a plurality of apertures (38) associated with the lenses of said lens array; and
d) a translator which provides relative motion between the wavefront sensor (38, 42, 44) and a wavefront (34) being measured by a distance corresponding to a non-integral number of apertures.

9. The sensor of claim 8, wherein the device for sensing the spot position is a charge-coupled device CCD (44).

10. The sensor of claim 8, wherein the device for sensing the spot position is an array of position sensitive detectors.

11. The sensor of claim 8, wherein the array of apertures comprises an absorbing or reflecting surface with holes therein which allow light to transmit through.

12. The sensor of claim 11, wherein the holes are rectangular in shape.

13. The sensor of claim 11, wherein the holes are trapezoidal in shape.

14. The sensor of claim 11, wherein the holes are slightly non-rectangular such that the normally parallel sides are tilted at a slight angle.

15. The sensor of claim 8, wherein the plurality of apertures is an array of lenses having a desired aperture shape.

16. The sensor of claim 15, wherein the lenses are rectangular.

17. The sensor of claim 15, wherein the lenses have trapezoidal apertures.

18. The sensor of claim 15, wherein the lenses are non-rectangular such that at least one pair of normally parallel sides are tilted.

Patentansprüche

1. Verfahren zum Verbessern der räumlichen Auflösung eines Hartmann-Wellenfrontsensors (38, 42, 44) mit einer Linsenanordnung (38), wobei das Verfahren gekennzeichnet ist durch:
   a) Bereitstellen von mehreren Öffnungen (38), die den Linsen der Anordnung zugeordnet sind; und
   b) Bereitstellen einer Relativbewegung zwischen dem Sensor (38, 42, 44) und einer abzustastenden Wellenfront (34) um einen Abstand, der einer nicht-ganzzahligen Anzahl von Öffnungen entspricht; und
   c) Bestimmen von Merkmalen der Wellenfront, die kleiner sind als eine Linse der Linsenanordnung gemäß einer Verschiebung des Ortes der Fokuspunkte zwischen Translationen.

2. Verfahren nach Anspruch 1, dadurch gekennzeichnet, daß die Translation im wesentlichen nur eine Bewegung des Wellenfrontsensors (38, 42, 44) umfaßt.

3. Verfahren nach Anspruch 1, dadurch gekennzeichnet, daß die Translation im wesentlichen nur eine Bewegung der Wellenfront (34) umfaßt.

4. Verfahren nach Anspruch 2, dadurch gekennzeichnet, daß die Translation sowohl eine Bewegung der Wellenfront (34) als auch des Wellenfrontsensors (38, 42, 44) umfaßt.

5. Verfahren nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß die Öffnungen harte Öffnungen sind.

6. Verfahren nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß das Bereitstellen das Ausbilden der mehreren Öffnungen auf einer Linsenanordnung (38) des Wellenfrontsensors umfaßt.

7. Verfahren nach einem der Ansprüche 1 bis 5, dadurch gekennzeichnet, daß das Bereitstellen das Ausbilden einer Linsenanordnung (38) umfaßt, wobei jedes Linsenelement eine gewünschte Öffnung aufweist.

8. Ein Hartmann-Wellenfrontsensor (38, 42, 44), folgendes umfassend:
   a) eine Linsenanordnung (38); und
   b) eine Vorrichtung (44) zum detektieren einer Position eines von einem Wellenfrontsensor (38, 42, 44) erzeugten Punktes, gekennzeichnet durch:
   c) mehrere Öffnungen (38), welche den Linsen der Linsenanordnung zugeordnet sind; und
   d) eine Verschiebevorrichtung, welche eine Relativbewegung zwischen dem Wellenfrontsensor (38, 42, 44) und einer Wellenfront (34) bereitstellt, die durch einen Abstand gegeben ist, der einer nicht-ganzzahligen Anzahl der Öffnungen entspricht.


10. Sensor nach Anspruch 8, dadurch gekennzeich-
net, daß die Vorrichtung zum Detektieren der Punktposition eine Anordnung von positionsensitiven Detektoren ist.


12. Sensor nach Anspruch 11, dadurch gekennzeichnet, daß die Löcher eine rechteckige Form aufweisen.


15. Sensor nach Anspruch 8, dadurch gekennzeichnet, daß die mehreren Öffnungen als eine Linsenanordnung mit einer gewünschten Form der Öffnungen ausgebildet sind.


17. Sensor nach Anspruch 15, dadurch gekennzeichnet, daß die Linsen trapezförmig ausgebildet sind.


Revendications

1. Procédé pour améliorer la résolution spatiale d'un détecteur de front d'onde de type Hartmann (38, 42, 44), comprenant un réseau de lentilles (38), le procédé étant caractérisé par les opérations consistant à :

(a) fournir une pluralité d'ouvertures (38) associées avec les lentilles dudit réseau de lentilles ;
(b) fournir un mouvement relatif entre le détecteur (38, 42, 44) et un front d'onde (34) devant être détecté, sur une distance correspondant à un nombre non entier d'ouvertures ; et
(c) déterminer des caractéristiques du front d'onde plus petites qu'une lentille du réseau de lentilles selon un changement de l'emplacement des spots focaux entre des translations.

2. Procédé selon la revendication 1, dans lequel ladite translation consiste essentiellement à déplacer seulement le détecteur de front d'onde (38, 42, 44).

3. Procédé selon la revendication 1, dans lequel ladite translation consiste essentiellement à déplacer seulement le front d'onde (34).

4. Procédé selon la revendication 1, dans lequel ladite translation comprend le déplacement à la fois du front d'onde (38, 42, 44) et du détecteur de front d'onde (34).

5. Procédé selon l'une quelconque des revendications précédentes, dans lequel les ouvertures sont des ouvertures dures.

6. Procédé selon l'une quelconque des revendications précédentes, dans lequel ladite opération consistant à fournir une pluralité d'ouvertures comprend la formation de la pluralité d'ouvertures sur un réseau de micro-lentilles (38) du détecteur de front d'onde.

7. Procédé selon l'une quelconque des revendications 1 à 5, dans lequel ladite opération consistant à fournir une pluralité d'ouvertures comprend la formation d'un réseau de micro-lentilles (38), chaque micro-lentille ayant une ouverture désirée.

8. Détecteur de front d'onde de type Hartmann (38, 42, 44) comprenant :

(a) un réseau de lentilles (38) ; et
(b) un dispositif (44) pour détecter une position d'un spot généré par le détecteur de front d'onde (38, 42, 44), le détecteur étant caractérisé par :
(c) une pluralité d'ouvertures (38) associées avec les lentilles dudit réseau de lentilles ; et
(d) un translateur qui fournit un mouvement relatif entre le détecteur de front d'onde (38, 42, 44) et un front d'onde (34) qui est mesuré, sur une distance correspondant à un nombre non entier d'ouvertures.

9. Détecteur selon la revendication 8, dans lequel le dispositif pour détecter la position des spots est un dispositif à couplage de charge CCD (44).

10. Détecteur selon la revendication 8, dans lequel le dispositif pour détecter la position des spots est un réseau de détecteurs sensibles à la position.

11. Détecteur selon la revendication 8, dans lequel le
réseau d’ouvertures comprend une surface absor- 
bante ou réfléchissante avec des trous dans celle- 
ici qui permettent à la lumière d’être transmise à tra-
vers eux.

12. Détecteur selon la revendication 11, dans lequel les 
troux sont de forme rectangulaire.

13. Détecteur selon la revendication 11, dans lequel les 
troux sont de forme trapézoïdale.

14. Détecteur selon la revendication 11, dans lequel les 
troux sont légèrement non-rectangulaires de telle 
sorte que les côtés normalement parallèles sont in-
clinés suivant un léger angle.

15. Détecteur selon la revendication 8, dans lequel la 
pluralité d’ouvertures est un réseau de lentilles 
ayant une forme d’ouverture désirée.

16. Détecteur selon la revendication 15, dans lequel les 
lentilles sont rectangulaires.

17. Détecteur selon la revendication 15, dans lequel les 
lentilles sont des ouvertures trapézoïdales.

18. Détecteur selon la revendication 15, dans lequel les 
lentilles sont non-rectangulaires de telle sorte qu’au 
moins une paire de côtés normalement parallèles 
est inclinée.