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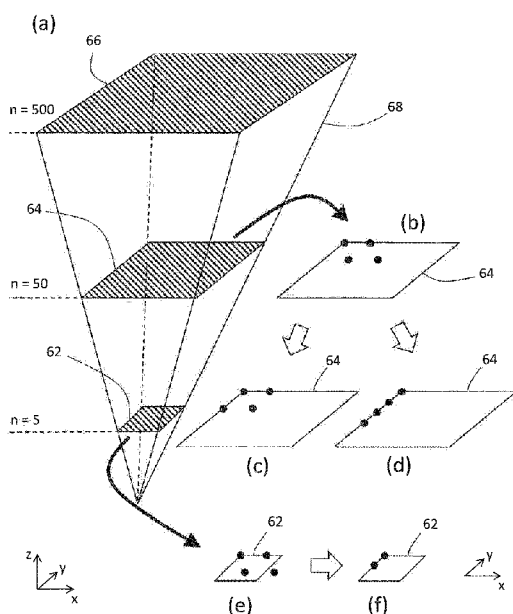


Fig. 7

(57) Abstract: An apparatus for producing a three-dimensional work piece is provided. The apparatus comprises a carrier configured to receive multiple layers of raw material and an irradiation unit configured to direct at least two laser sub-beams to predetermined sites of an uppermost layer of the raw material in order to solidify the raw material at the predetermined sites. The irradiation unit comprises a spatial light modulator arranged in the beam path of a laser beam and configured to split the laser beam into at least two laser sub-beams and a scanning unit for directing the at least two laser sub-beams to predetermined sites of the uppermost layer of the raw material. The apparatus further comprises a control unit configured to analyze three-dimensional work piece data of a work piece to be built and thereby analyze a geometry of a layer of said work piece to be built, generate control data for controlling the irradiation unit, wherein the control data comprises information indicative of a number of sub-beams generated by the spatial light modulator, and control the irradiation unit to perform irradiation of the raw material according to the control data. Further, a method for producing a three-dimensional work piece and a corresponding computer program product are provided.

ADDITIVE MANUFACTURING APPARATUS AND METHOD FOR PRODUCING A THREE-DIMENSIONAL WORK PIECE WITH MULTIPLE LASER SUB-BEAMS FROM A SPATIAL LIGHT MODULATOR SPLITTING A SINGLE LASER SOURCE

5 The present invention relates to an apparatus and a method for producing a three-dimensional work piece. In particular, the present invention is directed to an apparatus and a method for producing a three-dimensional work piece by solidifying multiple layers of raw material by means of laser radiation.

10 Powder bed fusion is an additive layering process by which pulverulent, in particular metallic and/or ceramic raw materials can be processed to three-dimensional work pieces of complex shapes. To that end, a raw material powder layer is applied onto a carrier and subjected to radiation (e.g., laser or particle radiation) in a site-selective manner in dependence on the desired geometry of the work piece that is to be produced. The radiation penetrating into the powder layer causes heating and  
15 consequently melting or sintering of the raw material powder particles. Further raw material powder layers are then applied successively to the layer on the carrier that has already been subjected to radiation treatment, until the work piece has the desired shape and size. Powder bed fusion may be employed for the production of prototypes, tools, replacement parts, high value components or medical prostheses, such as, for example, dental or orthopedic prostheses, on the basis of CAD data.  
20 Examples for powder bed fusion techniques include selective laser melting and selective laser sintering.

25 Besides the aforementioned powder bed fusion techniques, other additive manufacturing techniques are known according to which multiple layers of raw material are solidified by a laser beam, wherein the raw material is not necessarily provided in powder form but may be provided, e.g., as multiple layers of a fluid.

30 Within the context of such additive manufacturing techniques, process productivity becomes more and more important. In particular, with the possibility of producing larger work pieces due to the availability of larger process cylinders, it is important to reduce the time required for one build job. Process productivity can be measured, e.g., by calculating the melted or solidified volume of a produced work piece divided by the time required for the process.  
35

Recent developments are trying to solve the above problem by simultaneously irradiating the raw material with more than one laser beam. For example, one

5 approach consists in using a plurality of laser sources. Another approach involves splitting a laser beam into a plurality of laser sub-beams and to irradiate the laser sub-beams onto the raw material. In order to split the laser beam into the laser sub-beams, a diffractive optical element (DOE) may be used, as described in the patent EP 2 335 848 B1.

10 However, the solutions known from the prior art are either quite expensive and complex or they do not allow a high degree of flexibility, e.g., with regard to the number, beam shape, and/or arrangement of the generated laser beams.

The invention is directed at the object of providing an apparatus and a method, which solve the above-described problems and/or other related problems.

15 This object is addressed by an apparatus according to claim 1, by a method according to claim 13, and by a computer program product according to claim 14.

20 According to a first aspect, an apparatus for producing a three-dimensional work piece is provided. The apparatus comprises a carrier configured to receive multiple layers of raw material and an irradiation unit configured to direct at least two laser sub-beams to predetermined sites of an uppermost layer of the raw material in order to solidify the raw material at the predetermined sites. The irradiation unit comprises a spatial light modulator arranged in the beam path of a laser beam and configured to split the laser beam into at least two laser sub-beams and a scanning unit for directing the at least two laser sub-beams to predetermined sites of the uppermost layer of the raw material. The apparatus further comprises a control unit configured to analyze three-dimensional work piece data of a work piece to be built and thereby analyze a geometry of a layer of said work piece to be built, generate control data for controlling the irradiation unit, wherein the control data comprises information indicative of a number of sub-beams generated by the spatial light modulator, and control the irradiation unit to perform irradiation of the raw material according to the control data.

30 The following details concerning the apparatus of the first aspect may also be applicable to the method of the second aspect.

35 The apparatus may be an apparatus for selective laser melting or for selective laser sintering. The carrier may be movable in a vertical direction (up and down), such that

after a first layer of the work piece to be built is completely irradiated, the carrier can be lowered and a second layer of raw material (e.g., raw material powder) is applied onto the first layer and the second layer of the work piece can be irradiated and solidified. This process is continued until the work piece is finished. The carrier may comprise a substantially flat surface which defines a horizontal plane (in an x-y-plane of a Cartesian coordinate system). As described above, the carrier may be movable along the z-direction perpendicular to the x-y-plane.

The irradiation unit may comprise a laser source. However, the laser source may also be arranged outside the irradiation unit and guided to the irradiation unit by means of an optical fiber and/or one or more mirrors. The irradiation unit may further comprise a focus unit configured to change a focus position of the one or more laser sub-beams along a direction of the beam path (e.g., substantially along the z-direction). The focus unit may be arranged in the beam path upstream of the spatial light modulator. The irradiation unit may further comprise one or more optical components such as a beam expander, a collimator, an f-theta lens, etc. The irradiation unit may further comprise, upstream of the spatial light modulator, a polarization means configured to output linearly polarized light. The polarization means may comprise a waveplate (i.e., a  $\lambda/n$  plate) and/or a linear polarizer. The fact that the irradiation unit is configured to direct "at least two laser sub-beams" does not exclude that the irradiation unit is also configured to direct only one laser sub-beam to a predetermined site. In fact, it depends on a current configuration of the spatial light modulator, how many laser sub-beams are directed by the irradiation unit.

The spatial light modulator (also abbreviated as SLM) may comprise a dynamic (or tunable) diffractive optical element (DOE) or a different suitable spatial light modulator. Different kinds of spatial light modulators are known, wherein some of these spatial light modulators can be used for beam splitting and/or beam shaping. Here, the expression "beam splitting" refers to the ability of splitting a laser beam impinging on a surface of the spatial light modulator into two or more laser sub-beams. The expression "beam shaping" refers to the ability of controlling a beam profile of the one or more sub-beams coming from the spatial light modulator, such that it is possible to generate, e.g., a Gaussian beam profile or a top-hat beam profile. The spatial light modulator may be cooled by means of a known cooling technique (e.g., via air or via a liquid). Cooling of the spatial light modulator may be

especially advantageous in cases a high laser power is used, i.e., when the laser beam has a high laser power.

One known group of spatial light modulators that may be used includes liquid crystal on silicon (LCoS) devices. The use of LCoS devices and their advantages are described, e.g., in the following publications:

- Tobias Klerks, Stephan Eifel: Flexible beam shaping system for the next generation of process development in laser micromachining; 9th International Conference on Photonic Technologies LANE 2016;
- Lazarev, Grigory: Optimization of the Liquid Crystal on Silicon Technology for Laser Microprocessing Applications; 9th International Conference on Photonic Technologies LANE 2016;
- A. Gillner, M. Jüngst, P. Gretzki: Multi parallel ultrashort pulse laser processing; Lasers in Manufacturing Conference 2015;
- Strauß, Johannes; Häfner, Tom; Dobler, Michael; Heberle, Johannes; Schmidt, Michael: Evaluation and Calibration of LCoS SLM for Direct Laser Structuring with Tailored Intensity Distributions; 9th International Conference on Photonic Technologies LANE 2016; and
- LASER – Entwicklung und industrielle Anwendung; Heft Nr. 2, 29. Jahrgang, Mai/Juni 2015.

The scanning unit may comprise one or more movable mirrors configured to direct the one or more laser sub-beams to predefined sites of the uppermost layer of the raw material. The scanning unit may be configured such that all of the generated laser sub-beams coming from the spatial light modulator impinge on the same scanning mirror(s) and, therefore, are scanned together (i.e., substantially parallel) over the raw material. In other words, the scanning unit may be configured such that an arrangement of laser spots with respect to each other on the uppermost layer of raw material does not substantially change in case a configuration of the spatial light modulator does not change.

The control unit may be configured to control at least the spatial light modulator and the scanning unit. The control unit may be a main control unit of the apparatus. The control unit may comprise a processor and a memory on which instructions are stored which cause the processor to carry out the method steps described herein. In particular, the control unit may comprise a memory on which instructions are stored

which cause the processor to carry out the steps of analyzing, generating, and controlling defined with regard to the first aspect. The control unit may comprise a computer which is further configured to perform several control tasks for the apparatus including, e.g., preparation steps before a building process and/or control steps during the building process.

The three-dimensional work piece data may be CAD-data representative of a three-dimensional geometry of the work piece to be built. The layer of the work piece may correspond to a layer of the raw material that is to be irradiated and solidified during a building process. The control data may comprise machine control data. The control data may comprise information indicative of scanning vectors of the one or more laser sub-beams. The control data may not only be indicative of a number of sub-beams generated by the spatial light modulator but also of a shape (i.e., a beam profile) of said sub-beam(s). The control data may be used to control at least the scanning unit and the spatial light modulator.

The step of generating control data may be performed based on the step of analyzing, i.e., based on the analysis of the three-dimensional work piece data.

By defining a number of sub-beams to be generated by the spatial light modulator based on a geometry of a layer of the work piece, it is possible to flexibly adapt the number of sub-beams to the geometry of the work piece. Thus, a number of sub-beams generated by the spatial light modulator may change during the building process. For example, parts of the work piece that are required to have a higher quality (such as a mantle region of the work piece) can be solidified with a number of sub-beams that is known to result in a high quality, for example one single sub-beam. Other parts that shall be solidified quickly, can be irradiated with more than one sub-beam.

The control unit may be configured to define a core area of the analyzed layer and a mantle area surrounding the core area. The control data may be generated such that the irradiation unit is controlled to irradiate the mantle area with a first number of laser sub-beams and to irradiate the core area with a second number of laser sub-beams, wherein the second number is larger than the first number.

The mantle area may be defined to have a constant width. In other words, an inner borderline of the core area may have a constant distance from an edge of the

analyzed layer. The first number may be one or more, such that it is possible that the mantle area is irradiated with only one sub-beam and the core area is irradiated with more than one sub-beam.

5 The control unit may be configured to define at least one further mantle area between the core are and the mantle area. The control data may be generated such that the irradiation unit is controlled to irradiate the further mantle area with a third number of laser sub-beams, wherein the third number is larger than the first number and smaller than the second number.

10 For example, the first number may be one, the second number may be two and the third number may be three or more. The core area and the one or more mantle areas may be configured to cover the entire layer of the work piece to be built, such that each of the areas defines a number and arrangement of laser sub-beams with  
15 which the respective layer is irradiated in a following building process. In addition to a number and an arrangement, also a beam profile for the sub-beams may be defined for the core area and the one or more mantle areas.

20 By defining the above core area and the one or more mantle areas, it can be ensured that the mantle area has a high quality and, in particular, a high surface quality with regard to a surface of the work piece and that the core area can be irradiated faster than it would be possible with a single laser beam.

25 The control unit may be configured to generate the control data such that the irradiation unit is controlled to irradiate the layer of the work piece with a first number of laser sub-beams and to control the spatial light modulator to switch off one of the laser sub-beams when said one of the laser sub-beams reaches an edge of the layer.

30 Switching off the one of the laser sub-beams may mean, according to the present disclosure, that the spatial light modulator is controlled to generate one laser sub-beam less than before, wherein the remaining energy corresponding to the switched-off sub-beam may be distributed among the remaining laser sub-beams. Further possibilities of switching off one of the laser sub-beam may comprise reflecting the  
35 switched-off sub-beam into a beam dump or to absorb the remaining energy of the switched-off sub beam by the spatial light modulator.

By irradiating the layer as described above, an inner region (or core region) of the layer can be quickly irradiated with a plurality of sub-beams and an outer region (or mantle region) may be irradiated such that an outer shape of the layer (i.e., a contour) can be formed in the desired shape and quality.

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The control unit may be configured to generate the control data such that the irradiation unit is controlled to irradiate the layer of the work piece with the remaining laser sub-beam or the remaining laser sub-beams after the one of the laser sub-beams is switched off.

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An arrangement of the remaining laser sub-beams with regard to each other may be kept constant with respect to the time before and after switching off the one of the laser sub-beams.

15

The control unit may be configured to analyze the geometry of the layer of the work piece in relation to a direction of a gas flow within the apparatus, wherein the control unit is configured to generate the control data such that beam spots of the laser sub-beams are arranged such that no pair of the beam spots is arranged in a direction parallel to the gas flow.

20

The gas flow may be a flow of inert gas (e.g., nitrogen), wherein a direction of the gas flow is substantially parallel to the surface of the uppermost layer of raw material (i.e., parallel to the x-y-plane). When no pair (i.e., neither two nor more) of the beam spots is arranged in a direction parallel to the gas flow it can be ensured that no beam spot is influenced by melt residue generated by another beam spot and transported away by the gas flow.

25

The control unit may be configured to determine, for each layer of the work piece to be built, a number of laser sub-beams and an arrangement of beam spots of the laser sub-beams, wherein the number of laser sub-beams and the arrangement of the beam spots differs between at least two of the layers.

30

In other words, an optimal arrangement and number of beam spots can be determined for each of the layers of the work piece. Thereby it can be ensured that the work piece is generated with the required quality and process productivity.

35

The control unit may be configured to determine a first number of laser sub-beams for a first layer and a second number of laser sub-beams for a second layer, wherein an area of the second layer is larger than an area of the first layer and wherein the second number is larger than the first number.

5

For example, the above determination may comprise analyzing whether a given arrangements of beam spots fits into the analyzed layer and when the given arrangement does not fit into the analyzed layer, at least one of the beam spots is removed and/or the arrangement of the beam spots is changed such that the new arrangement fits into the analyzed layer. An analysis of another layer may start again by analyzing whether the given arrangement of beam spots fits into the analyzed layer.

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The control unit may be configured to analyze the geometries of layers of two different work pieces to be built next to each other, wherein the layers belong to a same layer of raw material, and wherein the number of laser sub-beams and the arrangement of beam spots are determined for the layers of both work pieces.

20

In that case, at least two work pieces are planned to be built next to each other. Here, not only a layer of one of these work pieces is analyzed but both layers of the work pieces (within the same layer of raw material) are analyzed and the beam spots are optimized for both layers and, therefore, for both work pieces.

25

The control unit may be configured to generate the control data for controlling the irradiation unit, wherein the control data comprises information indicative of a beam shape of at least one of the sub-beams.

30

Information indicative of the beam shape of the at least one of the sub-beams may, for example, include information regarding a width of the respective sub-beam and/or a beam profile such as, e.g., a Gaussian profile or a top-hat profile. In other words, a beam profile of each of the generated sub-beams may be controlled.

35

A zoom homogenizer may be arranged in the beam path of the laser beam, upstream of the spatial light modulator. As an alternative, the apparatus may comprise a vertical-cavity surface-emitting laser, VCSEL, configured to generate the laser beam.

The zoom homogenizer may be an optical element configured to shape a laser beam (having, e.g., a round or Gaussian beam profile) into a substantially rectangular beam profile. The intensity within said substantially rectangular beam profile may be substantially homogenous. The VCSEL may be configured to emit a substantially rectangular beam profile. The substantially rectangular beam profile of the zoom homogenizer or of the VCSEL may be used to irradiate a rectangular surface of the spatial light modulator.

The control unit may be configured to control the irradiation unit to split the laser beam into a predefined number of laser sub-beams and to simultaneously irradiate, with each of the laser sub-beams, a layer of a corresponding work piece, wherein the irradiated layers of the work pieces are in the same layer of raw material and have substantially the same shape.

By applying the above technique, one generated work piece may be "cloned" and a plurality of substantially identical work pieces can be simultaneously generated next to each other. All of the generated sub-beams may be directed and reflected by the same scanning unit of the irradiation unit. In that way, the plurality of work pieces can be generated by only moving one scanning unit.

The apparatus may further comprise a device for suppressing a zero-order diffraction of the spatial light modulator. The device may be arranged in the beam path behind the spatial light modulator (i.e., downstream of the spatial light modulator). The device may comprise at least one of the following elements: a beam block, means for moving the zero-order diffraction axially, a phase compression means, a means for causing destructive interference, and a means for applying a frequency based algorithm to any phase pattern. The beam block may be configured as described in Maxim Shusteff et al.: Additive Fabrication of 3D Structures by Holographic Lithography. The means for moving the zero-order diffraction axially may be configured as described in Marco Polin et al.: Optimized holographic optical traps and/or Susanne Zwick et al.: Dynamic holography using pixelated light modulators. The phase compression means may be configured as described in Jinyang Liang, Michael F. Becker: Phase Compression Technique to Suppress the Zero-Order Diffraction from a Pixelated Spatial Light Modulator (SLM). The means for causing destructive interference may be configured as described in Alexander Jesacher, Martin J. Booth: Parallel direct laser writing in three dimensions with spatially dependent aberration correction and/or Darwin Palima and Vincent Ricardo Daria:

Holographic projection of arbitrary light patterns with a suppressed zero-order beam. The means for applying a frequency based algorithm to any phase pattern may be configured as described in Emiliano Ronzitti et al.: LCoS nematic SLM characterization and modeling for diffraction efficiency optimization, zero and ghost orders  
5 suppression.

According to a second aspect, a method for producing a three-dimensional work piece is provided. The method is carried out with an apparatus comprising a carrier configured to receive multiple layers of raw material and an irradiation unit  
10 configured to direct at least two laser sub-beams to predetermined sites of an uppermost layer of the raw material in order to solidify the raw material at the predetermined sites. The irradiation unit comprises a spatial light modulator arranged in the beam path of a laser beam and configured to split the laser beam into at least two laser sub-beams and a scanning unit for directing the at least two laser sub-  
15 beams to predetermined sites of the uppermost layer of the raw material. The method comprises analyzing three-dimensional work piece data of a work piece to be built and thereby analyzing a geometry of a layer of said work piece to be built, generating control data for controlling the irradiation unit, wherein the control data comprises information indicative of a number of sub-beams generated by the spatial  
20 light modulator, and controlling the irradiation unit to perform irradiation of the raw material according to the control data.

Each of the details discussed above with regard to the apparatus of the first aspect may also apply to the method of the second aspect. The same holds for the  
25 computer program product described below.

The method may further comprise defining a core area of the analyzed layer and a mantle area surrounding the core area and irradiating the mantle area with a first number of laser sub-beams and irradiating the core area with a second number of  
30 laser sub-beams, wherein the second number is larger than the first number.

The method may further comprise defining at least one further mantle area between the core are and the mantle area and irradiating the further mantle area with a third number of laser sub-beams, wherein the third number is larger than the first number  
35 and smaller than the second number.

The method may further comprise irradiating the layer of the work piece with a first number of laser sub-beams and controlling the spatial light modulator to switch off one of the laser sub-beams when said one of the laser sub-beams reaches an edge of the layer.

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The method may further comprise irradiating the layer of the work piece with the remaining laser sub-beam or the remaining laser sub-beams after the one of the laser sub-beams is switched off.

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The method may further comprise analyzing the geometry of the layer of the work piece in relation to a direction of a gas flow within the apparatus and arranging beam spots of the laser sub-beams such that no pair of the beam spots is arranged in a direction parallel to the gas flow.

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The method may further comprise determining, for each layer of the work piece to be built, a number of laser sub-beams and an arrangement of beam spots of the laser sub-beams, wherein the number of laser sub-beams and the arrangement of the beam spots differs between at least two of the layers.

20

The method may further comprise determining a first number of laser sub-beams for a first layer and a second number of laser sub-beams for a second layer, wherein an area of the second layer is larger than an area of the first layer and wherein the second number is larger than the first number.

25

The method may further comprise analyzing the geometries of layers of two different work pieces to be built next to each other, wherein the layers belong to a same layer of raw material, and wherein the number of laser sub-beams and the arrangement of beam spots is determined for the layers of both work pieces.

30

The control data may comprise information indicative of a beam shape of at least one of the sub-beams.

A zoom homogenizer may be arranged in the beam path of the laser beam, upstream of the spatial light modulator. As an alternative, the apparatus may comprise a vertical-cavity surface-emitting laser, VCSEL, generating the laser beam.

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The method may further comprise splitting the laser beam into a predefined number of laser sub-beams and simultaneously irradiating, with each of the laser sub-beams, a layer of a corresponding work piece, wherein the irradiated layers of the work pieces are in the same layer of raw material and have substantially the same shape.

5

According to a third aspect, a computer program product stored on a computer-readable storage medium is provided. The computer program product comprises computer-readable instructions for causing a computer to carry out the method of the second aspect.

10

Preferred embodiments of the invention are described in greater detail with reference to the appended schematic drawings, wherein

15

Fig. 1 shows a schematic side view of an apparatus according to the present disclosure;

Fig. 2a shows a schematic side view of an irradiation unit of a first alternative embodiment of an apparatus according to the present disclosure;

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Fig. 2b shows a schematic side view of an irradiation unit of a second alternative embodiment of an apparatus according to the present disclosure;

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Fig. 3 shows a schematic top view of a layer of a work piece to be built, wherein the layer is analyzed and a core area and one mantle area are defined;

Fig. 4 shows a schematic top view of a layer of a work piece to be built, wherein the layer is analyzed and a core area and three mantle areas are defined;

30

Fig. 5 shows a top view of a layer of a work piece to be built, wherein a laser sub-beam is switched off during an irradiation process of the layer;

Fig. 6 shows a schematic top view of two suitable arrangements of laser spots with regard to a direction of a gas flow; and

35

Fig. 7 shows a schematic perspective view of a work piece to be built, wherein a number and an arrangement of laser spots of sub-beams is optimized based on a shape of a corresponding layer of the work piece.

Fig. 1 shows a schematic perspective side view of an apparatus for producing a three-dimensional work piece according to the present disclosure. The apparatus comprises a carrier 10 having a rectangular built surface parallel to the x-y-plane. In the representation shown in Figure 1, a first layer ( $n = 1$ ) of raw material powder 12 has been applied onto the carrier 10 by a powder application device (not shown) of the apparatus. Since only one layer of raw material powder 12 has been applied onto the carrier 10, this first layer ( $n = 1$ ) represents an uppermost layer of raw material. This uppermost layer is irradiated and partially solidified by one or more laser sub-beams 14, 16 as will be described below. After the first layer has been irradiated in a desired shape, the carrier 10 can be lowered by means of a vertical carrier movement device (not shown) of the apparatus. After that, a second layer ( $n = 2$ ) of raw material powder 12 is applied onto the first layer ( $n = 1$ ) and the second layer is irradiated. This process is continued until the final work piece is completely solidified.

The apparatus further comprises an irradiation unit 18. The irradiation unit 18 comprises a laser beam source 20, a spatial light modulator 22, and a scanning unit 24. Optionally, the irradiation unit 18 further comprises one or more additional optical elements 26 that are arranged between the laser beam source 20 and the spatial light modulator 22. The optical element 26 shown in Figure 1 may comprise one or more of a VARIO scan element, a focusing unit configured to adjust a focus position along the beam path of the sub-beams 14, 16, a beam expander, etc.

In the embodiment shown in Figure 1, the spatial light modulator 22 comprises a liquid crystal on silicon (LCoS) device. The spatial light modulator 22 can be controlled to modulate an incoming laser beam 27 such that the incoming laser beam 27 is split into a plurality of laser sub-beams 16. However, the spatial light modulator 22 can also be controlled not to split the incoming laser beam 27 and to output only one laser sub-beam 14. In Figure 1 both of these cases are shown in one figure, wherein at a first time  $t_1$  the spatial light modulator 22 is controlled to have a configuration in which four sub-beams 16 are output and at a second time  $t_2$  the spatial light modulator 22 is controlled to have a configuration in which one sub-beam 14 is output. In addition to outputting one sub-beam 14 and four sub-beams 16, the spatial light modulator 22 can also be controlled to output other numbers of sub-beams as will be discussed below. Further, the spatial light modulator 22 can be controlled to adjust a shape (i.e., a beam profile) of each of the sub-beams 14, 16.

For example, the spatial light modulator 22 can be controlled such that the sub-beams 14, 16 have a Gaussian profile or a top-hat profile.

5 A cooling device (not shown) may optionally be provided for cooling the spatial light modulator 22 by means of a known cooling technique (e.g., via air or via a liquid). Cooling of the spatial light modulator 22 may be especially advantageous in cases a high laser power is used, i.e., when the incoming laser beam 27 has a high laser power.

10 The apparatus further comprises a control unit 28 for controlling the irradiation unit 18. More precisely, the control unit 28 can communicate with each of the elements 20, 22, 24, and 26 of the irradiation unit 18 and is configured to transmit control signals to each of these elements. For example, the control unit 28 can switch on and off the laser beam source 20. Further, the control unit 28 controls the spatial  
15 light modulator 22 and is configured to transmit control signals to the spatial light modulator 22, which define a number and/or a beam profile of the sub-beams 14, 16 output by the spatial light modulator 22. Also the scanning unit 24 is controlled by the control unit 28, wherein the control unit 28 can control a position (i.e., a position with regard to the x-y-plane) of the one or more sub-beams 14, 16 on the uppermost  
20 layer of the raw material powder 12. For example, in case the optical element 26 comprises a focusing unit, the control unit 28 can control a focus position of the sub-beams 14, 16 in a direction of the beam path of the sub-beams (i.e., substantially in the z-direction). Further, the control unit 28 controls other functions of the apparatus, such as a vertical movement of the carrier 10.

25 The control unit 28 is also configured to analyze three-dimensional work piece data of a work piece to be built. The work piece data may be, e.g., CAD-data and, more precisely, a CAD-file. In order to analyze the work piece data, the control unit 28 considers the individual layers of the work piece to be built. Each layer of the work  
30 piece corresponds to a layer of raw material powder 12, wherein only the irradiated and solidified parts of the layer of raw material powder 12 become a layer of the work piece.

35 Based on the analysis of the layers of the work piece to be built, the control unit 28 generates control data for controlling the irradiation unit 18 according to the control data. For example, the control data is indicative of a number of sub-beams 14, 16

output by the spatial light modulator 22. Further, the control data is indicative of an arrangement of the sub-beams 16 with respect to each other.

In the exemplary representation of Figure 1, a contour 30 of a work piece is shown. The contour 30 is representative of an outer shape of the first layer of the work  
5 piece. Before the irradiation process of the first layer is started, the control unit 28 analyzes the first layer of the work piece to be built and, in particular, a geometry thereof. As will be discussed in detail below, this analysis may result in control data for performing various scan strategies with one or more sub-beams 14, 16. In the  
10 example shown in Figure 1, the control unit 28 has analyzed the first layer of the work piece to be built and has determined that an inner part (i.e., a core area) of the work piece shall be irradiated with four laser sub-beams 16 in a first irradiation process comprising the time  $t_1$ . Further, the control unit 28 has determined that a contour 30 (i.e., a mantle area) of the analyzed layer of the work piece shall be  
15 irradiated with a single irradiation spot from a single sub-beam 14 in a second irradiation process comprising the time  $t_2$ . The control unit 28 generates the respective control data defining the number of sub-beams 14, 16 and scan vectors 32 for these sub-beams 14, 16. In other words, the control unit 28 defines at which time which location of the layer of the work piece shall be irradiated with how many  
20 sub-beams 14, 16.

In this way, every layer of the work piece to be built is analyzed by the control unit 28 and respective control data is generated for each layer. This process leads to control data for an optimized building process of the work piece, wherein time and  
25 quality aspects can be considered and optimized.

Figure 2 shows a schematic side view of an irradiation unit 18 of an alternative embodiment of an apparatus for producing a three-dimensional work piece according to the present disclosure. Apart from the irradiation unit 18, the configuration of the  
30 apparatus of the embodiment of Figure 2 is the same as described with regard to Figure 1. Similar to the embodiment of Figure 1, the irradiation unit 18 of Figure 2 comprises a laser beam source 20, a spatial light modulator 22, and a scanning unit 24.

Between the laser beam source 20 and the spatial light modulator 22, a polarization means 33 and a zoom homogenizer 34 are arranged. The polarization means 33 is  
35 configured to receive the laser beam 27 from the laser beam source 20 and to output

a linearly polarized laser beam 27. The polarization means 33 may comprise a waveplate (i.e., a  $\lambda/n$  plate). Performing a linear polarization of the laser beam 27 may be advantageous or even necessary in case the spatial light modulator 22 is configured to receive a linearly polarized laser beam 27. This may be the case, in particular, for liquid crystal on silicon (LCoS) devices. Therefore, in case an LCoS device is used for the spatial light modulator 22 in the embodiment of Figure 1, also a polarization means may be provided in the embodiment of Figure 1, for example at the position of the optical element 26.

The zoom homogenizer 34 is configured to perform beam shaping of the laser beam 27. In particular, the zoom homogenizer is configured to reshape the incoming laser beam 27 (which may have a Gaussian beam profile) to a laser beam 27 having a substantially rectangular beam profile. The substantially rectangular beam profile may have a substantially homogenous intensity distribution over the entire rectangular profile. The rectangular laser beam 27 is then directed to impinge onto the spatial light modulator 22, which has a rectangular surface. The rectangular laser beam 27 is positioned such that the rectangular surface of the spatial light modulator 22 is fully illuminated.

As an alternative to the zoom homogenizer 34 shown in Figure 2, a laser beam source 20 may be used which already outputs a laser beam 27 with a substantially rectangular beam profile. An example of such a laser beam source 20 may be a vertical-cavity surface-emitting laser (VCSEL).

By illuminating the spatial light modulator 22 with a rectangular beam profile (as explained above, e.g., by using a zoom homogenizer 34) it is possible to irradiate the spatial light modulator 22 with a higher laser power, because the laser power is homogeneously distributed over the entire surface of the spatial light modulator 22. Thereby, a higher laser power and an equally distributed laser power of the individual sub-beams 14, 16 can be obtained.

Fig. 2b shows a schematic side view of an irradiation unit of a second alternative embodiment of an apparatus according to the present disclosure. According to the second alternative embodiment, a device 35 for suppressing a zero-order diffraction of the spatial light modulator 22 is arranged in the beam path of the apparatus, behind the spatial light modulator 22 (i.e., downstream of the spatial light modulator 22).

The rest of the apparatus may be configured as discussed above with regard to the embodiment shown in Fig. 1. Optionally, as described with regard to the first alternative embodiment shown in Fig. 2a, a polarization means 33 and/or a zoom homogenizer 34 may be arranged in the beam path of the apparatus (see Fig. 2b, wherein the dashed lines of elements 33 and 34 indicate that these elements are optional).

The device 35 for suppressing a zero-order diffraction of the spatial light modulator 22 is configured to suppress a zero-order deflection caused by deflection at the spatial light modulator 22. deflection of the laser beam 27 at the spatial light modulator 22 causes different orders of diffraction, which are numbered 0 to n. By definition, the zero-order diffraction represents an intensity maximum, which might be undesirable in some cases. In other words, it might be advantageous to suppress this intensity maximum corresponding to a zero-order diffraction of the spatial light modulator 22.

The device 35 may comprise at least one of the following elements: a beam block, means for moving the zero-order diffraction axially, a phase compression means, a means for causing destructive interference, and a means for applying a frequency based algorithm to any phase pattern. The beam block may be configured as described in Maxim Shusteff et al.: Additive Fabrication of 3D Structures by Holographic Lithography. The means for moving the zero-order diffraction axially may be configured as described in Marco Polin et al.: Optimized holographic optical traps and/or Susanne Zwick et al.: Dynamic holography using pixelated light modulators. The phase compression means may be configured as described in Jinyang Liang, Michael F. Becker: Phase Compression Technique to Suppress the Zero-Order Diffraction from a Pixelated Spatial Light Modulator (SLM). The means for causing destructive interference may be configured as described in Alexander Jesacher, Martin J. Booth: Parallel direct laser writing in three dimensions with spatially dependent aberration correction and/or Darwin Palima and Vincent Ricardo Daria: Holographic projection of arbitrary light patterns with a suppressed zero-order beam. The means for applying a frequency based algorithm to any phase pattern may be configured as described in Emiliano Ronzitti et al.: LCoS nematic SLM characterization and modeling for diffraction efficiency optimization, zero and ghost orders suppression.

Figure 3 shows an example of analyzing a geometry of a layer of the work piece to be built. Figure 3(a) shows a top view of a contour 30 of a layer of the work piece to be built. The geometry of the work piece is derived from the three-dimensional work piece data (e.g., a CAD-file). The shape of the layer of the work piece is analyzed by the control unit 28 and segmented into a mantle area 36 and a core area 38. The mantle area 36 surrounds the core area 38 and has a constant thickness  $d$ . In other words, a borderline between the core area 38 and the mantle area 36 has a constant distance  $d$  from the contour 30 of the work piece. The control unit 28 generates control data that defines that the mantle area 36 is irradiated with a single laser spot 40 of a single sub-beam and that the core area 38 is irradiated with a 3x3 matrix 42 of nine laser spots of nine sub-beams. As shown in Figure 3(a), the nine laser spots are arranged in a rectangular matrix having a rectangular shape with a diagonal width  $d3 \times 3$ . The control unit 28 defines scanning vectors both for the single laser beam 14 and for the 3x3 matrix 42 within the mantle area 36 and the core area 38, respectively.

Figure 3(b) shows a method of using a grid 44 for determining sections of the layer of the raw material powder 12 to be irradiated with a single laser spot 40 and sections to be irradiated with a 3x3 matrix 42. This method may be regarded as a simple way to implement the goal shown in Figure 3(a), namely the irradiation of the mantle area 36 with a single laser beam 40 and the irradiation of the core area 38 with a 3x3 matrix 42.

In the step of analyzing the layer of the work piece to be built, a grid 44 is applied onto the layer of the work piece and rectangles 46 (hatched) of the grid 44 that overlap at least a section of the mantle area 36 are defined to belong to a first group. Rectangles 48 (cross-hatched) that overlap the work piece but do not overlap any section of the mantle area 36 are defined to belong to a second group. Control data is then generated by the control unit 28 which defines that in the rectangles 46 of the first group, irradiation is performed with a single laser beam 40 and in the rectangles 48 of the second group, irradiation is performed with a 3x3 matrix 42. Of course, instead of the 3x3 matrix, any other kind of  $n \times n$  matrix can be used, wherein  $n$  is a number larger than 1.

In a further improvement of the method shown in Figure 3(b), rectangles 50 of the second group can be identified, which are not directly adjacent to another rectangle 48 of the second group (i.e., they do not have a common grid line as borderline).

These rectangles 50 can be assigned to the first group, such that in these rectangles 50 irradiation of a single laser spot 40 is performed.

5 Figure 4 shows how a layer of a work piece to be built is segmented into a core area 38 and three mantle areas 36a, 36b, and 36c. The core area 38 is surrounded by the third mantle area 36c, which again is surrounded by the second mantle area 36b. The second mantle area 36b is surrounded by the first mantle area 36a, which comprises a contour 30 of the layer of the work piece. In the example shown in Figure 4, the control unit generates control data which defines that the first mantle area 36a is irradiated with a single laser spot, the second mantle area 36b is irradiated with two laser spots, the third mantle area 36c is irradiated with three laser spots, and the core area 38 is irradiated with four laser spots. As an alternative to the number of laser spots mentioned above, the first mantle area 36a can be irradiated with a single laser spot, the second mantle area 36b can be irradiated with four laser spots, the third mantle area 36c can be irradiated with nine laser spots, and the core area 38 can be irradiated with sixteen laser spots.

Figure 5 shows a schematic example of a method performed by the control unit 28, wherein individual laser spots are switched off during the irradiation of the work piece. As described in the above embodiments, an analysis of a geometry of the layer of the work piece is performed by the control unit 28 in advance and control data is generated which leads to the following control of the irradiation spots 52, 54, 56, and 58. The laser spots 52, 54, 56, and 58 are moved together over the layer of the work piece, wherein an arrangement of the laser spots 52, 54, 56, and 58 with respect to each other stays constant. This scanning of the laser spots is performed by the scanning unit 24. In the example shown in Figure 5, the laser spots 52, 54, 56, and 58 are moved in the y-direction. When the first laser spot 52 of the laser spots 52, 54, 56, and 58 reaches a contour 30 of the work piece, this laser spot is switched off by the spatial light modulator 22. The movement of the other laser spots 54, 56, and 58 is continued until a second one (54) of the laser spots reaches the contour 30. This laser spot 54 is then also switched off, etc. By using this method, a shape of the contour 30 can be generated or maintained only by switching off individual laser spots, wherein an inner part of the layer of the work piece can be quickly irradiated with more than one laser spot.

Switching off the one of the laser sub-beams may mean, according to the present disclosure, that the spatial light modulator is controlled to generate one laser sub-

beam less than before, wherein the remaining energy corresponding to the switched-off sub-beam may be distributed among the remaining laser sub-beams. Further possibilities of switching off one of the laser sub-beam may comprise reflecting the switched-off sub-beam into a beam dump or to absorb the remaining energy of the switched-off sub beam by the spatial light modulator

Figure 6 shows how an arrangement of laser spots 60 can be defined under consideration of a direction of a gas stream within the apparatus. The gas stream may be a stream of inert gas parallel to the x-y-plane and, in particular, parallel to the x-direction as shown in Figure 6. The gas stream is configured to transport away melt residue generated by the one or more melting processes of the one or more sub-beams. When two laser spots 60 are arranged in parallel to the direction of the gas flow, melt residue generated by one of the laser spots 60 is blown into the direction of the other laser spot 60 and can negatively affect the melting process of this other laser spot (see Figure 6(a)). Therefore, the laser spots 60 can be arranged as shown in Figures 6(b) or (c). In both Figures 6(b) and (c) no pair of laser spots 60 is arranged in parallel to the direction of the gas flow (x-direction). In the example shown in Figure 6(b) a second line of laser spots 60 is shifted in a direction perpendicular to the direction of the gas flow. In the example shown in Figure 6(c), all laser spots 60 are arranged along a direction perpendicular (or at least not parallel) to the direction of the gas flow.

Figure 7 shows how the irradiation of a plurality of layers 62, 64, and 66 of a work piece 68 can be optimized. Figure 7(a) shows the work piece 68 to be built. Each layer of the work piece 68 is analyzed by the control unit 28. In the following, only the layers 62 ( $n = 5$ ), 64 ( $n = 50$ ), and 66 ( $n = 500$ ) are exemplarily discussed. However, a similar analysis can be performed for each layer  $n = 1$  to  $n = 500$  of the work piece 68. As shown in Figure 7(e) the layer 62 is analyzed and it is determined whether a predefined arrangement of laser spots is suitable for the irradiation of this layer 62. However, as shown in Figure 7(e) the predefined arrangement comprising four laser spots does not fit into the layer 62 and, therefore, the arrangement is discarded. Instead, as indicated by the arrow between Figures 7(e) and (f), the arrangement shown in Figure 7(f) is used, which only comprises two laser spots arranged next to each other. Therefore, corresponding control data is generated for the work piece 68 to be generated which defines that the layer 62 is irradiated with an arrangement of laser spots as shown in Figure 7(f).

As shown in Figure 7(b) also layer 64 is analyzed. Even though the arrangement of laser spots shown in Figure 7(b) fits into the layer 64, it is also discarded because it is not optimal for irradiating the layer 64. One reason for that is that it is not possible to irradiate the entire layer 64 with the arrangement of laser spots shown in  
5 Figure 7(b). Therefore, one of the arrangements of laser spots shown in Figures 7(c) or (d) is considered. Both of these arrangements are better suitable for irradiating the layer 64 because the entire area 64 can be irradiated with the laser spots of the respective arrangement. An analysis of the layer 66 of the work piece 68 to be built is performed similar to the analysis of layers 62 and 64.

10 For each layer, a number and an arrangement of laser spots can be determined which optimizes an irradiation time of the respective layer. In case individual laser spots are switched on or off during the irradiation of one of the layers, also a switching time of the spatial light modulator 22 can be taken into account (i.e., a  
15 time required for switching on or off one of the sub-beams). Determining a number and an arrangement of laser spots for each layer can be regarded as an optimization problem, wherein an irradiation time of each layer is minimized.

20 In case a plurality of work pieces is to be built next to each other, a plurality of layers of the work pieces may be present in one layer of the raw material powder 12. In that case a first layer of a first work piece may have a different geometry than a second layer of a second work piece in the same layer of the raw material powder 12. Therefore, a number and an arrangement of laser spots can be changed between the irradiation of the first layer and the second layer. In the corresponding  
25 optimization problem, a switching time of the spatial light modulator 22 can be taken into account.

30 The aforementioned technique can also be used for building more than one substantially identical work piece next to each other. By splitting the laser beam 27 into more than one sub-beams, the same work piece can be "cloned" and a plurality of substantially identical work pieces can be built next to each other. In that case, a distance between the laser spots on the uppermost layer of raw material powder 12 has to be quite large. Since all of the laser spots are simultaneously moved by the scanning unit 24 over the layer of raw material powder 12, an arrangement of the  
35 laser spots with respect to each other is maintained. By performing the above method, a plurality of work pieces can be quickly build on the same carrier 10. Since the movement of the scanning unit 24 has only to be controlled for one work piece,

the control of this building process is simplified. In the context of the above-described cloning method, the work piece is also analyzed in advance and control data for controlling the irradiation unit is generated. The control data defines that more than one irradiation spots are generated and that these irradiation spots are spaced apart from each other at a distance that one work piece for each laser spot is generated.

With the technique discussed above, one or more work pieces can be generated in an efficient manner under consideration of time and quality requirements. In other words, a build process for one or more work pieces can be optimized, wherein the capabilities of the spatial light modulator 22 are advantageously used.

## Claims

- 5 1. An apparatus for producing a three-dimensional work piece comprising:  
a carrier (10) configured to receive multiple layers of raw material (12);  
an irradiation unit (18) configured to direct at least two laser sub-beams (16)  
to predetermined sites of an uppermost layer of the raw material (12) in order to  
solidify the raw material (12) at the predetermined sites, wherein the irradiation unit  
10 (18) comprises:  
a spatial light modulator (22) arranged in the beam path of a laser  
beam (27) and configured to split the laser beam (27) into at least two laser sub-  
beams (16); and  
a scanning unit (24) for directing the at least two laser sub-beams (16)  
15 to predetermined sites of the uppermost layer of the raw material (12); and  
a control unit (28) configured to:  
analyze three-dimensional work piece data of a work piece to be built  
and thereby analyze a geometry of a layer of said work piece to be built;  
generate control data for controlling the irradiation unit (18), wherein  
20 the control data comprises information indicative of a number of sub-beams (14, 16)  
generated by the spatial light modulator (22); and  
control the irradiation unit (18) to perform irradiation of the raw  
material (12) according to the control data.
- 25 2. The apparatus of claim 1, wherein the control unit (28) is configured to define  
a core area (38) of the analyzed layer and a mantle area (36; 36a) surrounding the  
core area (38), and wherein the control data is generated such that the irradiation  
unit (18) is controlled to irradiate the mantle area (36; 36a) with a first number of  
laser sub-beams and to irradiate the core area (28) with a second number of laser  
30 sub-beams, wherein the second number is larger than the first number.
3. The apparatus of claim 2, wherein the control unit (28) is configured to define  
at least one further mantle area (36b, 36c) between the core area (38) and the  
mantle area (36a), wherein the control data is generated such that the irradiation  
unit (18) is controlled to irradiate the further mantle area (36b, 36c) with a third  
35 number of laser sub-beams, wherein the third number is larger than the first number  
and smaller than the second number.

4. The apparatus of claim 1, wherein the control unit (28) is configured to generate the control data such that the irradiation unit (18) is controlled to irradiate the layer of the work piece with a first number of laser sub-beams (52, 54, 56, 58) and to control the spatial light modulator (22) to switch off one of the laser sub-beams when said one of the laser sub-beams reaches an edge (30) of the layer.

5. The apparatus of claim 4, wherein the control unit (28) is configured to generate the control data such that the irradiation unit (18) is controlled to irradiate the layer of the work piece with the remaining laser sub-beam or the remaining laser sub-beams after the one of the laser sub-beams is switched off.

6. The apparatus of any of claims 1 to 5, wherein the control unit (28) is configured to analyze the geometry of the layer of the work piece in relation to a direction of a gas flow within the apparatus, and wherein the control unit (28) is configured to generate the control data such that beam spots (60) of the laser sub-beams are arranged such that no pair of the beam spots (60) is arranged in a direction parallel to the gas flow.

7. The apparatus of any of claims 1 to 6, wherein the control unit (28) is configured to determine, for each layer of the work piece to be built, a number of laser sub-beams and an arrangement of beam spots of the laser sub-beams, wherein the number of laser sub-beams and the arrangement of the beam spots differs between at least two of the layers.

8. The apparatus of claim 7, wherein the control unit (28) is configured to determine a first number of laser sub-beams for a first layer and a second number of laser sub-beams for a second layer, wherein an area of the second layer is larger than an area of the first layer and wherein the second number is larger than the first number.

9. The apparatus of claim 7 or 8, wherein the control unit (28) is configured to analyze the geometries of layers of two different work pieces to be built next to each other, wherein the layers belong to a same layer of raw material (12), and wherein the number of laser sub-beams and the arrangement of beam spots is determined for the layers of both work pieces.

10. The apparatus of any of claims 1 to 9, wherein the control unit (28) is configured to generate the control data for controlling the irradiation unit (18), wherein the control data comprises information indicative of a beam shape of at least one of the sub-beams.

5

11. The apparatus of any of claims 1 to 10, wherein a zoom homogenizer (34) is arranged in the beam path of the laser beam (27), upstream of the spatial light modulator (22), or wherein the apparatus comprises a vertical-cavity surface-emitting laser, VCSEL, configured to generate the laser beam (27).

10

12. The apparatus of any of claims 1 to 11, wherein the control unit (28) is configured to control the irradiation unit (18) to split the laser beam (27) into a predefined number of laser sub-beams and to simultaneously irradiate, with each of the laser sub-beams, a layer of a corresponding work piece, wherein the irradiated layers of the work pieces are in the same layer of raw material (12) and have substantially the same shape.

15

13. The apparatus of any of claims 1 to 12, wherein the apparatus further comprises:

20 a device (35) for suppressing a zero-order diffraction of the spatial light modulator (22).

14. A method for producing a three-dimensional work piece with an apparatus comprising:

25 a carrier (10) configured to receive multiple layers of raw material (12);  
an irradiation unit (18) configured to direct at least two laser sub-beams (16) to predetermined sites of an uppermost layer of the raw material (12) in order to solidify the raw material (12) at the predetermined sites, wherein the irradiation unit (18) comprises:

30 a spatial light modulator (22) arranged in the beam path of a laser beam (27) and configured to split the laser beam (27) into at least two laser sub-beams (16); and

a scanning unit (24) for directing the at least two laser sub-beams (16) to predetermined sites of the uppermost layer of the raw material (12), wherein the method comprises:

35

analyzing three-dimensional work piece data of a work piece to be built and thereby analyzing a geometry of a layer of said work piece to be built;

generating control data for controlling the irradiation unit (18), wherein the control data comprises information indicative of a number of sub-beams generated by the spatial light modulator (22); and

5 controlling the irradiation unit (18) to perform irradiation of the raw material (12) according to the control data.

15. A computer program product stored on a computer-readable storage medium, comprising computer-readable instructions for causing a computer to carry out the method of claim 14.

10

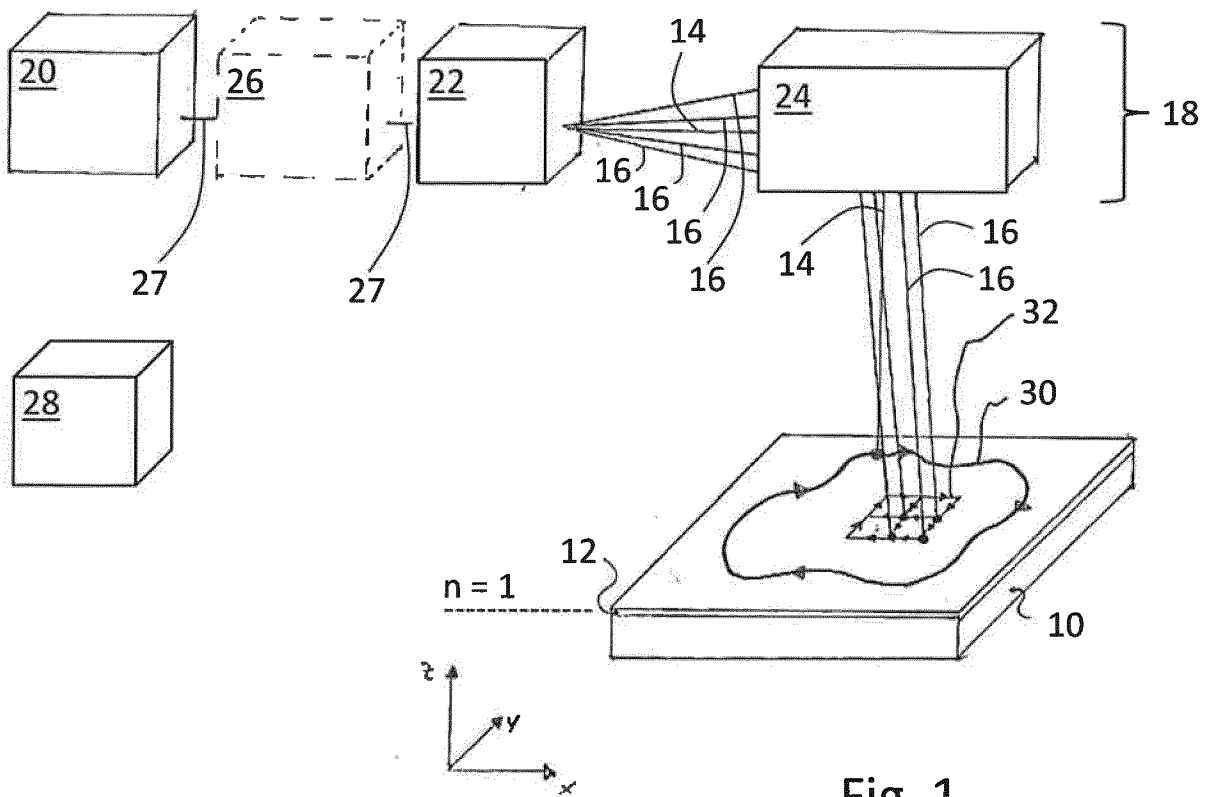


Fig. 1

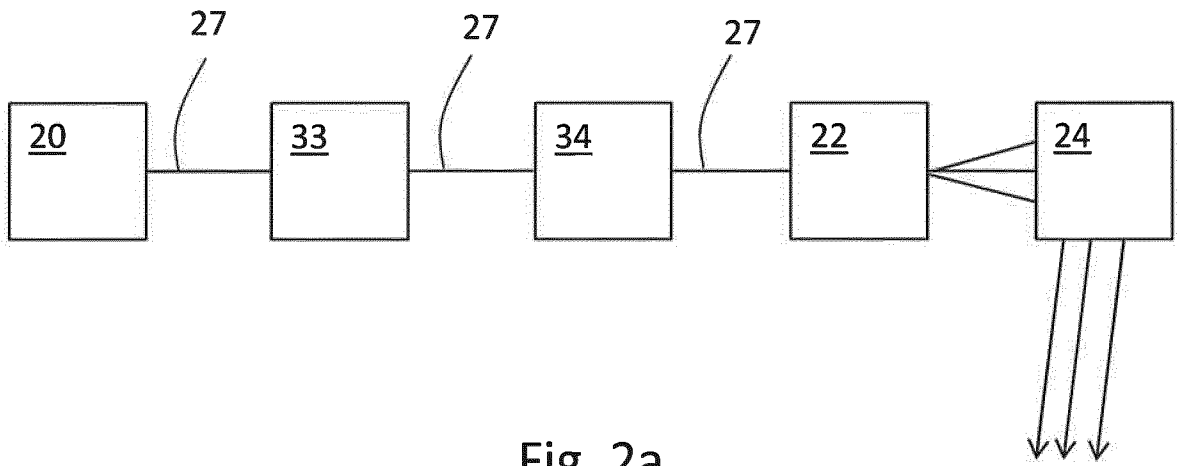


Fig. 2a

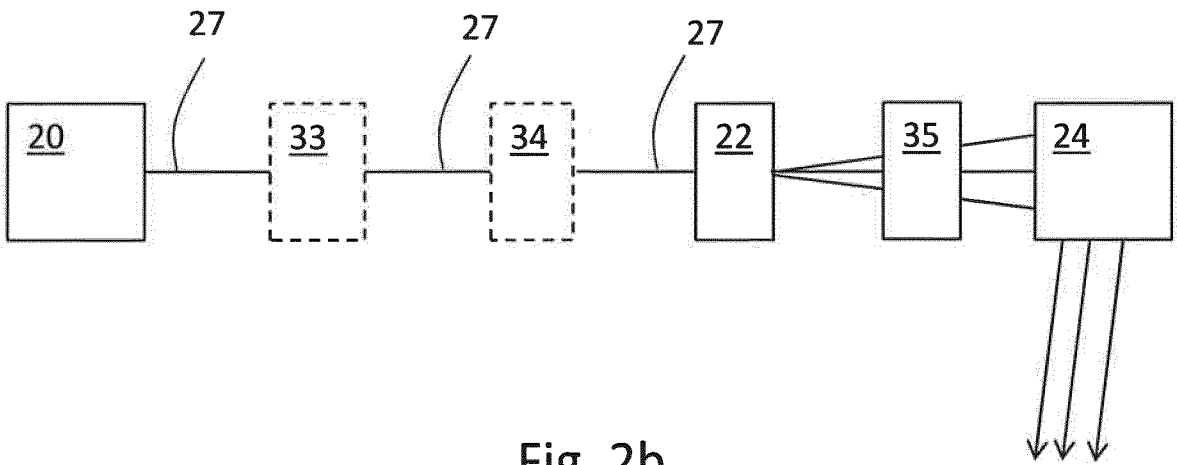


Fig. 2b

3/6

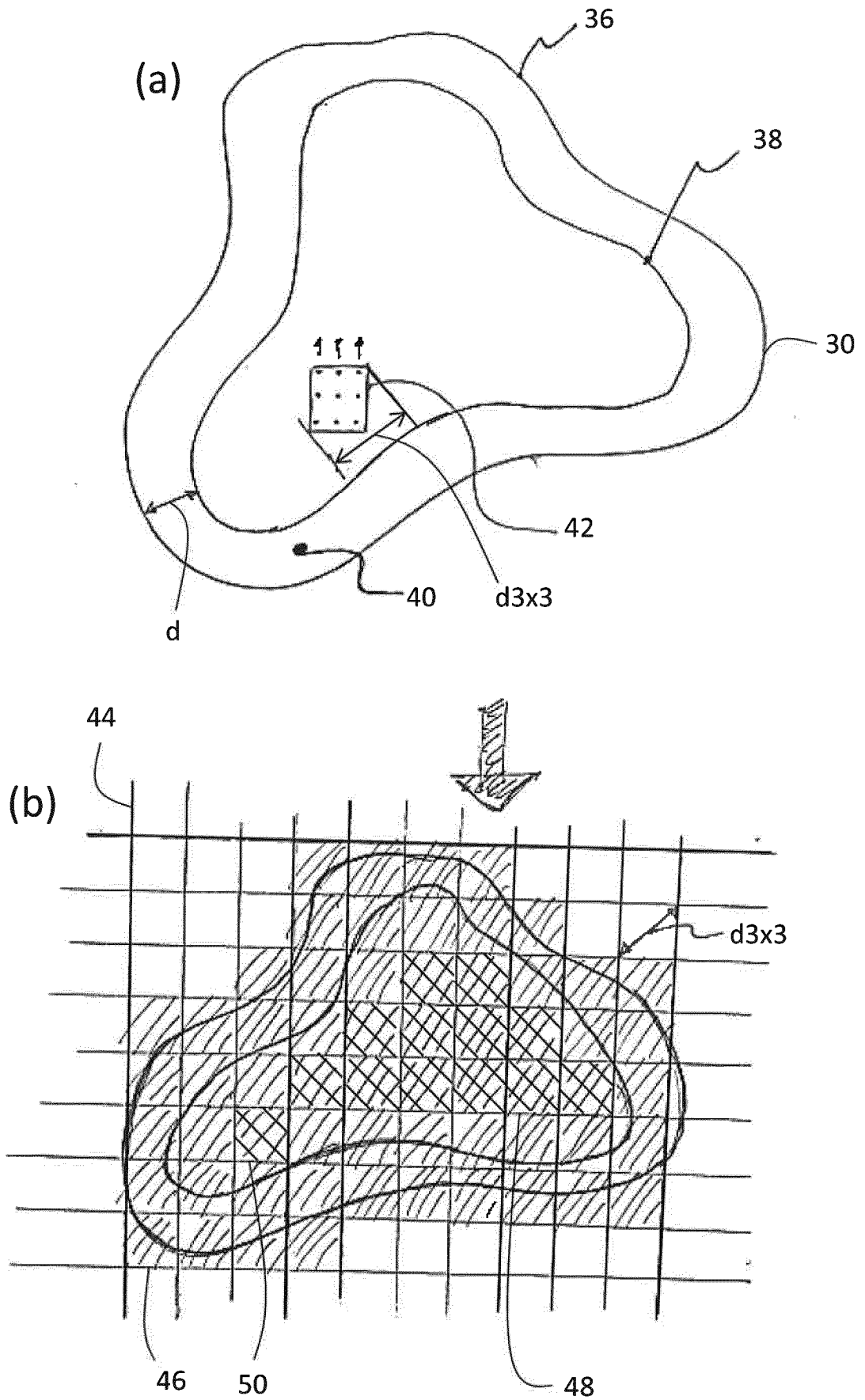


Fig. 3

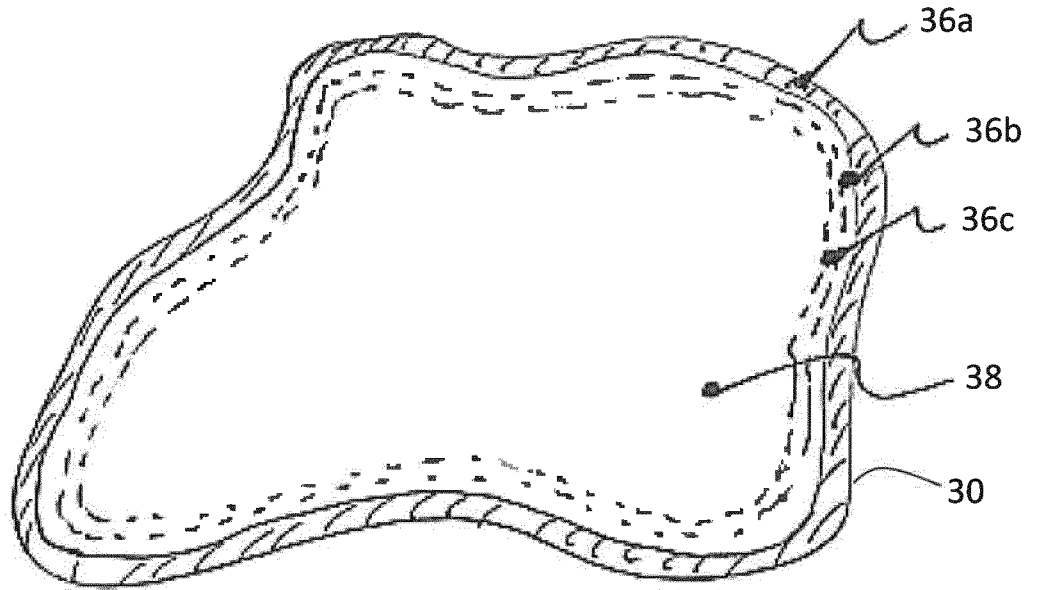


Fig. 4

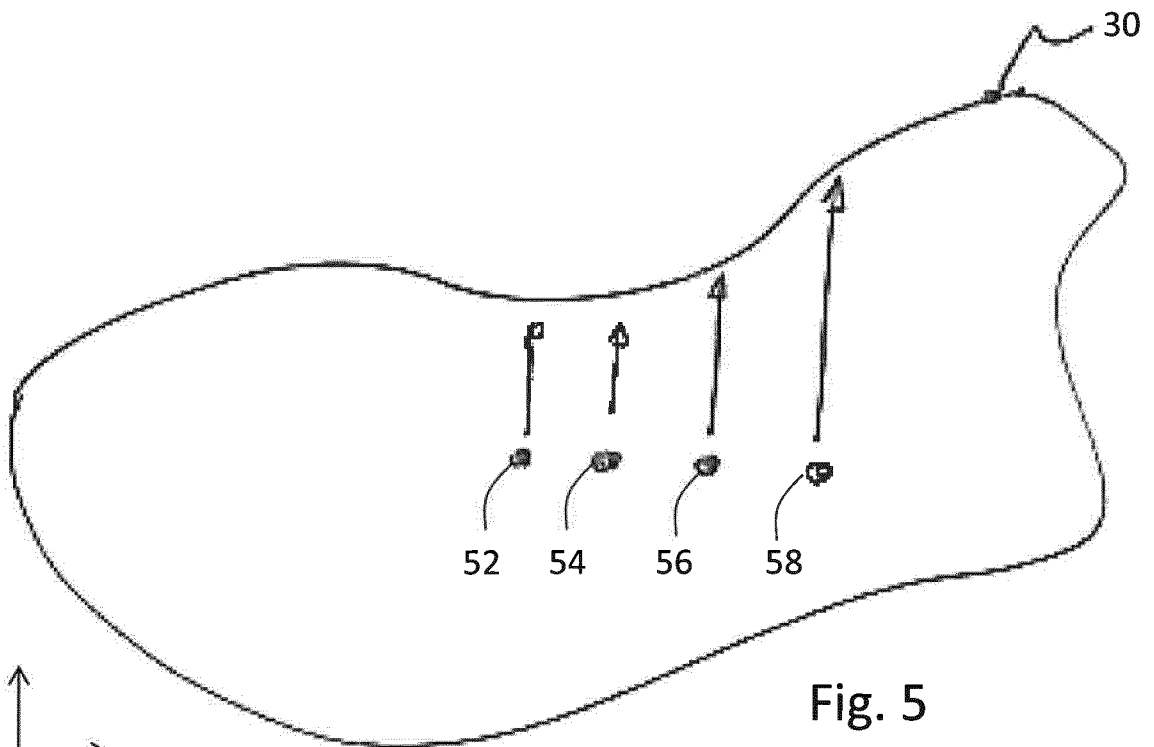


Fig. 5

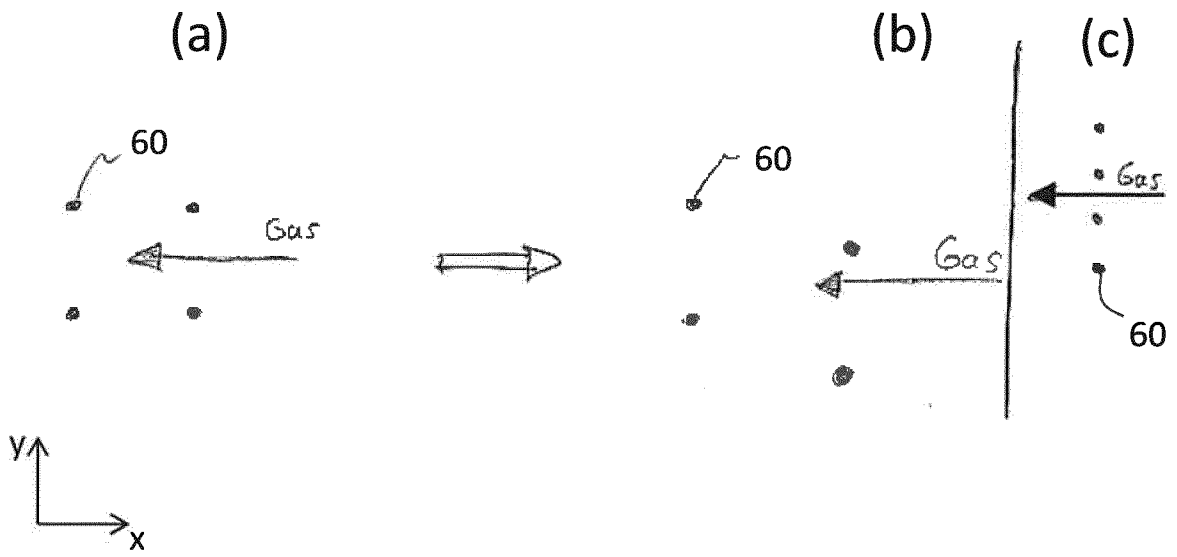


Fig. 6

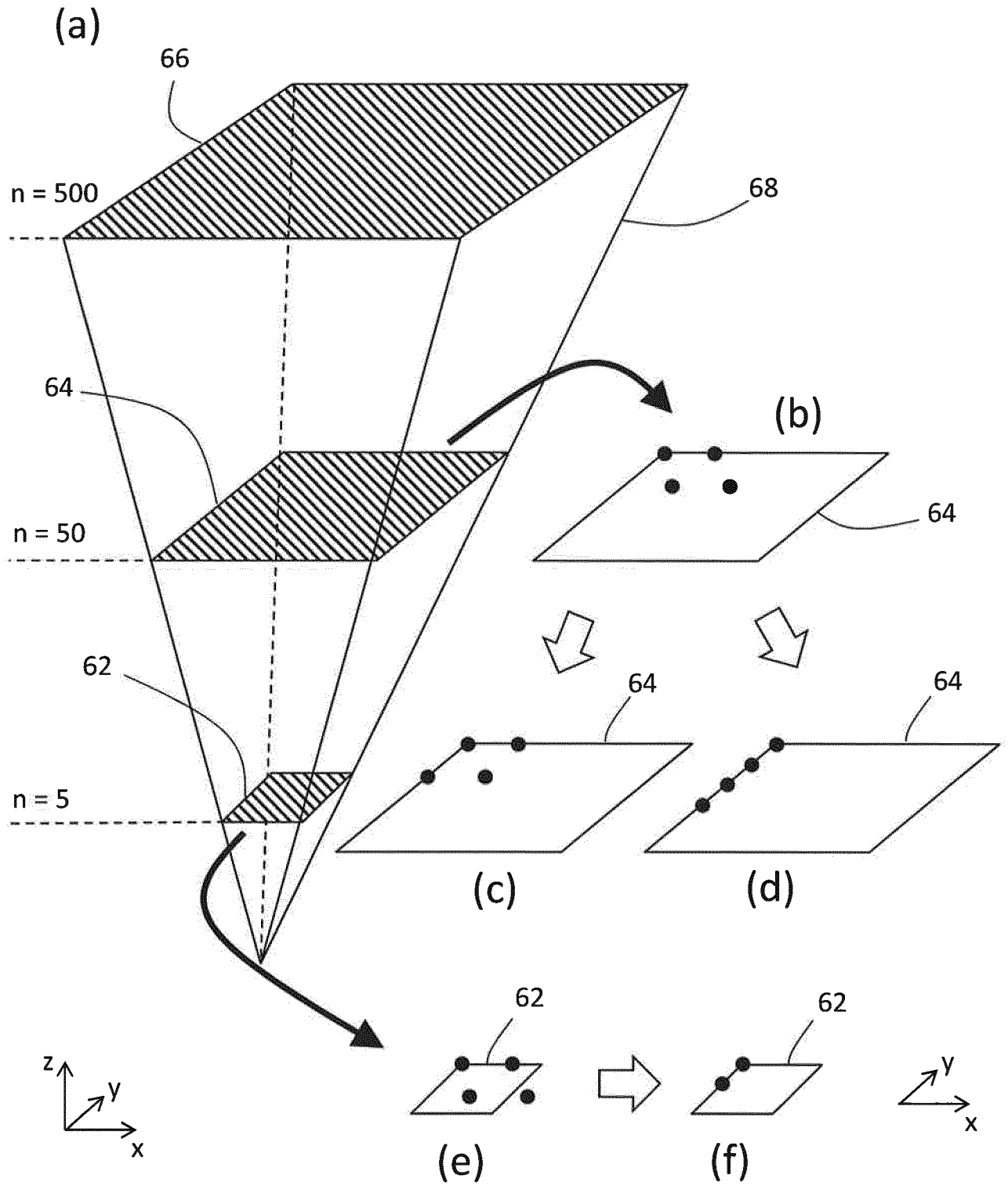


Fig. 7

INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2018/051422

A. CLASSIFICATION OF SUBJECT MATTER  
 INV. B29C64/153 B33Y10/00 B33Y30/00 B29C64/20 B22F3/105  
 G03F7/20  
 ADD.  
 According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED  
 Minimum documentation searched (classification system followed by classification symbols)  
 B22F B29C B33Y B28B G03F

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
 EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2013/064706 A1 (SCHWARZE DIETER [DE] ET AL) 14 March 2013 (2013-03-14) paragraphs [0002], [0007], [0009], [0011] - [0012], [0014] - [0016], [0017], [0034] - [0037], [0039] - [0040]; figures 1-2, 5	1,10-12, 14,15 2-6
Y	US 5 536 467 A (REICHLER JOHANNES [DE] ET AL) 16 July 1996 (1996-07-16) column 1, line 22 - column 2, line 24; figure 1 column 2, lines 39-48, 55-59; claims 1-3	2,3
Y	US 2016/136730 A1 (MCMURTRY DAVID ROBERTS [GB] ET AL) 19 May 2016 (2016-05-19) paragraphs [0007], [0037], [0039] - [0041], [0044] - [0046], [0048]; figures 2-4	4-6
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Further documents are listed in the continuation of Box C.

See patent family annex.

\* Special categories of cited documents :

- "A" document defining the general state of the art which is not considered to be of particular relevance
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- "O" document referring to an oral disclosure, use, exhibition or other means
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- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search <b>7 November 2018</b>	Date of mailing of the international search report <b>14/11/2018</b>
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Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer <b>Lemoisson, Fabienne</b>
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## INTERNATIONAL SEARCH REPORT

International application No  
PCT/EP2018/051422

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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