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(54) **Title:** TACTILE SENSOR

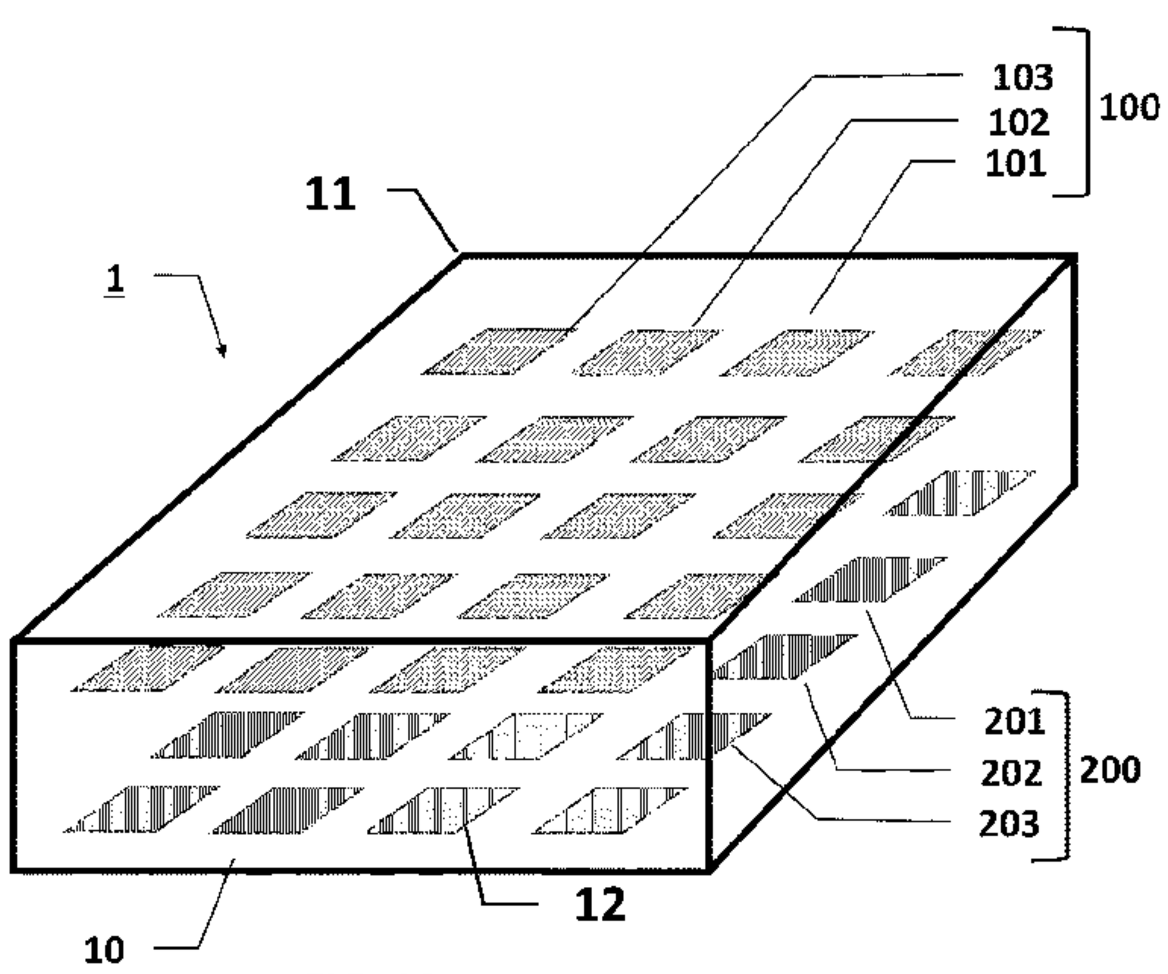

FIG. 1A

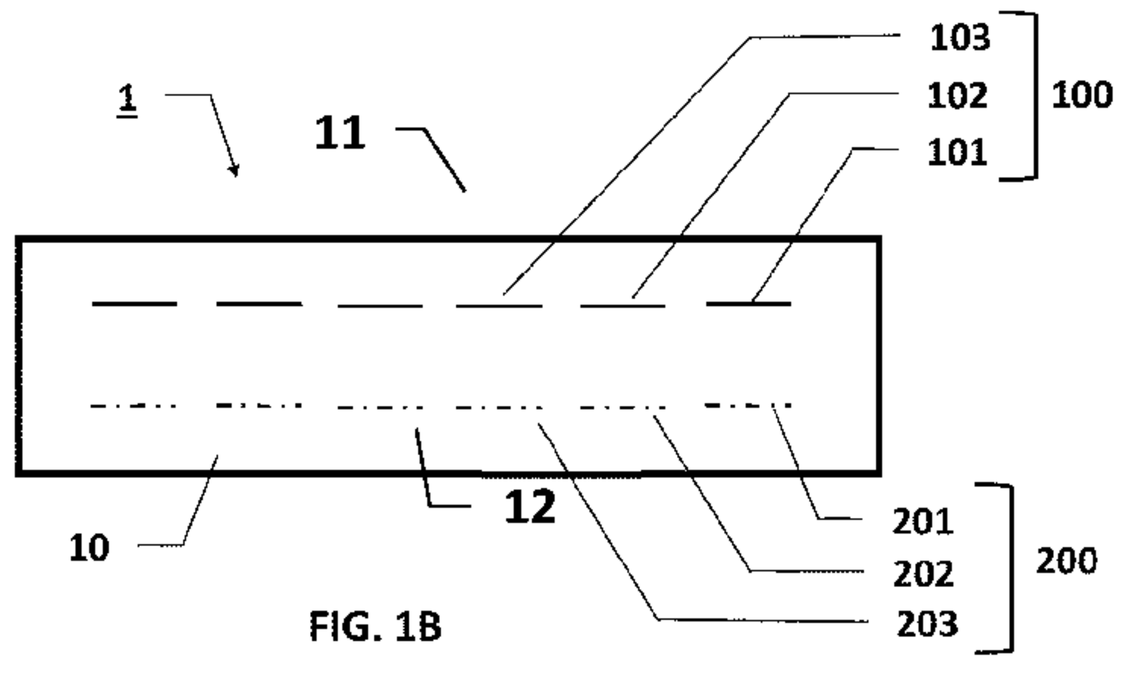

FIG. 1B

(57) **Abstract:** Disclosed is a tactile sensor for use in the skin of a finger gripper system of a robot. The tactile sensor comprises a single slab of an elastomeric material having a top surface and a bottom surface. Furthermore, the tactile sensor comprises a first array of force sensitive elements embedded in the slab adjacent to the top surface, and a second array of force sensitive elements embedded in the slab adjacent to the bottom surface. Advantageously, the tactile sensor allows establishing the direction of the force exerted by an object on the robot's skin, respectively sensor slab. For, as the object exerts a force on the robot skin, the distribution of the force as detected by the force sensitive elements in the first or top array will be shifted relative to the force distribution detected in the second or bottom array. Moreover, with measuring the position and direction of the force distribution, the invention also allows a robot to gain knowledge of the hardness of the object's surface.

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— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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Tactile Sensor

The invention relates to a tactile sensor, having tactile sensory capabilities, amongst other useable for a robot according to the preamble of the independent claim 1. The invention further relates to a finger gripper system for a robot comprising such a tactile sensor. Moreover, the invention relates to a robot comprising a finger gripper system comprising a tactile sensor.

Background to the invention

Nowadays, grippers of robots perform manipulation tasks mostly with additional visual guidance, or on a predefined path. This leads to restrictions, high complexity, and loss of speed. Preferably procedure for instructing robots to perform such manipulation tasks allow flexibility and are applicable for many objects to be manipulated. Manipulation executed by a gripper of a robot may be similar to the grasping of a human being, which is highly effective. The human can manipulate an object without looking and just unconsciously thinking about it. Spinning a pen between the finger tips or on top of the fingers is a highly complex yet simple exercise for a human. The majority of people can perform this action successfully with their eyes closed. In contrast, such an exercise is presently impossible for a robot due to a lack of mechano-receptive abilities.

Accordingly, it is an objective of the invention to allow a finger gripper system of a robot to measure the position and orientation of an object (such as a pen) and predict in which position/orientation it will be, respectively how the object's position/orientation needs to be corrected. Thus, enabling the robot to performance similar highly complex exercises as described above.

Summary

The invention achieves this and other objectives by providing a tactile sensor comprising a slab of elastomeric material, for forming a robot's skin, having a top surface and a bottom surface; a first array of force sensitive elements embedded in the slab adjacent to the top surface; and a second array of force sensitive elements embedded in the slab adjacent to the bottom surface.

Advantageously, the sensor according to the invention, respectively the slab, forms part of a robot skin in which the force sensitive elements allow not only to measure the position of an object. The two arrays of sensitive elements, each at a different depth in the slab or skin also allow establishing the direction of the force exerted by an object on the robot skin, respectively sensor slab. For, as the object exerts a force of the robot skin, the force distribution as detected by the force sensitive elements in the first or top array will be shifted relative to the force distribution detected in the second or bottom array. Moreover, with measuring the position and direction of the force distribution, the invention also allows a robot to gain knowledge on the hardness of the object's surface. Furthermore, embedding the two arrays in a single or unitary slab of elastomeric material advantageously prevents the formation of air gaps between the arrays. The inventors have established that such air gaps occur in case the robot skin would consist of a first layer embedding the first array on top of a second layer embedding the second array. Or in case the robot skin would consist of three layers: a first sensor array layer, a second sensor layer, and an intermediate elastomeric material layer coupling the two sensor arrays. Such air gaps especially occur when phalanges of a robot finger gripper system move relative to each other.

In an embodiment, the tactile sensor further comprising a third array of force sensitive elements embedded in the slab intermediate between the first and second arrays. Advantageously, the inventors have established that such a third array is beneficial in determining the position and orientation of “spiky” objects. In this respect, a “spiky” object is defined as an object which can not be rolled or tilted over a flat reference surface such that any point on the object’s surface can be brought into contact with the reference surface. Examples are the Kepler-Poinsot polyhedra, concave polygons, but also a pen with a clip or a mug with an ear.

In an embodiment, the force sensitive elements of the arrays are aligned in a direction perpendicular to the top surface. Advantageously, stacking the individual force sensitive elements on top of each other establishes a simple cubic unit-cell style macro-array of elements embedded in the slab. This allows a simple even distribution of the fore sensitive elements throughout the slab for establishing the force distribution inside the robot skin exerted by the object. Such a simple cubic style macro-array can be created both with two arrays (top and bottom arrays) as well as with three arrays (top, middle, and bottom array). Alternatively, a body-centred cubic unit cell style macro-array can be created using three arrays. In this latter embodiment, the force sensitive elements of the first and second arrays are aligned in a direction perpendicular to the top surface while the force sensitive elements of the third array are dis-aligned with the elements of the first and second arrays. Advantageously, this improves determining the position and orientation of “spiky” objects.

In an embodiment, the arrays are each subdivided in a first partition and a second partition. Thus, the first or top array has a first and a second partition, as does the second or bottom array, as well as the optional third or middle array. Advantageously, the partitions of each array are arranged such that all (two or three) first partitions are “on top” of each other, and all (two or three) second partitions are “on top” of each other. This advantageously allows associating the first partitions with a first phalange of a finger in a robot’s finger gripper system, and the second partitions with a second (adjacent) phalange of the finger.

In an embodiment, the tactile sensor further comprising a groove in the top surface of the slab. Advantageously, the grove is positioned between the first partitions and the second partitions of the arrays of force sensitive elements. Beneficially, the groove can be positioned near or on top of a joint connecting a first phalange of a robot's finger with a second phalange, especially when the first partitions are associated with the first phalange and the second partitions are associated with the second phalange.

In an embodiment, the slab, rather than forming a flat sensor, forms a three-dimensional shape. In particular, the slab is curved around an axis aligned essentially parallel to the top and bottom surfaces. In this configuration, the sensor can be incorporated into the skin of a robot's finger extending not only over the length of the finger, but also at right angles around at least a part of the finger. Advantageously, this allows sensing a sliding motion of an object over the finger, respectively a dynamic balancing movement of the object. In an embodiment, the first and second partitions may be further partitioned, so that a phalange may be associated with a "left", a "middle", and a "right" sub-partition. Advantageously this allows manipulating an object positioned between the fingers of a multi-finger gripper system.

In an embodiment, the force sensitive elements are force sensitive resistors. As an example, the force sensitive resistors are made of graphene platelets with comb electrodes. Advantageously, such force resistive sensors show very little hysteresis. Moreover, these sensors may be produced using screen printing techniques allowing flexibility in the array design.

A cording to another aspect, the invention provides a finger gripper system for a robot comprises a sensor according to the first aspect. Advantageously, the finger system comprises a finger having a first phalange and a second phalange connected by a joint allowing the first and second phalanges to move relative to each other, wherein the sensor extends over the first and second phalanges. In an embodiment, the sensor extending over the first and second phalanges comprises groove in the top surface of the slab, and the groove is located adjacent to the joint. Advantageously, this allows curling-up the finger of the gripper system while avoiding the formation of a bulge in the elastomeric material displacing the force sensitive elements in the top, middle and bottom arrays relative to each other, especially those elements near the joint. Such a displacement would have a detrimental effect on the accuracy of an object’s position and orientation measurement. In yet another embodiment, the arrays in the sensor extending over the first and second phalanges are each subdivided in a first partition and a second partition, and the first partitions are associated with the first phalange and the second partitions are associated with the second phalange. Advantageously, this allows providing feedback on placement and position of an object relative to the finger (or fingers of the gripper system), as well as allows providing feedback on sliding movements of the object, respectively a dynamic balancing movement of the object (such as a pen) between the fingers.

In yet another aspect, the invention provides a robot comprising a finger gripper system according to the second aspect.

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter. Appreciate, however, that these embodiments may not be construed as limiting the scope of protection for the invention. They may be employed individually as well as in combination.

Brief description of the drawings

The invention will be explained in more detail in the following with reference to embodiments and to the drawings. There are shown in the schematic drawings:

Fig. 1A: a perspective view of tactile sensor according to the invention

Fig. 1B: a side view of the tactile sensor according to the invention

Fig. 2A a side view of an embodiment of the tactile sensor comprising a top array, a middle array, and a bottom array in which the force sensitive elements form a simple cubic style macro-array

Fig. 2B a side view of an embodiment of the tactile sensor comprising a top array, a middle array, and a bottom array in which the force sensitive elements form body-centred cubic unit cell style macro-array

Fig. 3 a perspective view of an embodiment of the tactile sensor comprising a first and second partition of the top array and a first and second partition of the bottom array.

Fig. 4 a side view of an embodiment of the tactile sensor comprising a groove in the top surface

Those skilled in the art will appreciate that elements in the drawings are illustrated for simplicity and clarity and have not necessarily been drawn to scale. For example, the dimensions of some of the elements in the drawings may be exaggerated relative to other elements to help improve understanding of the various embodiments of the invention. Furthermore, the terms “first”, “second”, and the like herein, if any, are used inter alia for distinguishing between similar elements and not necessarily for describing a sequential or chronological order. Moreover, the terms “front”, “back”, “top”, “bottom”, “up”, “down”, “over”, “under”, “proximal”, “distal”, and the like in the description and/or in the claims, if any, are generally employed for descriptive purposes and not necessarily for comprehensively describing exclusive relative position. Also, the term “engagement feature” may also constitute a “disengagement feature”. Skilled artisans will therefore understand that any of the preceding terms so used may be interchanged under appropriate circumstances such that various embodiments of the invention described herein, for example, are capable of operation in other configurations and/or orientations than those explicitly illustrated or otherwise described.

Detailed description

Figures 1A and **1B** provide a schematic perspective and side view of a tactile sensor 1. The tactile sensor comprises a slab 10 of an elastomeric material. Preferably the slab is arranged to be unitary and may form the skin of a robot’s finger. Examples of elastomeric materials are rubber, silicone, polyurethane, and gelatinous substances such as agar and polyvinyl alcohol. Embedded in slab 10 the tactile sensor comprises a first array 100 of force sensitive elements 101, 102, 103, and a second array 200 of force sensitive elements 201, 202, 203. The first array 100 is located adjacent the top surface 11 of slab 10, while the second array 200 is located adjacent the bottom surface 12 of slab 10. Typically slab 10 has a thickness of 3 to 5 mm. Moreover, typically the distance between top array 100 and bottom array 200 is in the range 0.5 to 1.0 mm, while the size of each force sensitive element is typically 5x5 mm^2.
In the embodiment of the tactile sensor 1 shown in **Figures 2A** and **2B** the sensor comprises a third array 300 of force sensitive elements 301, 302, 303 embedded in slab 10 intermediate between the first and second arrays.

The force sensitive elements 101, ..., 303 may be based on several physical mechanisms. As examples a change in capacitance, resistance, and electrical charge can be used in the sensor. Thus, the force sensitive elements may be piezoresistive sensor elements, capacitive sensor elements, piezoelectric sensor elements, quantum tunnel effect sensor elements, resistor sensor elements. As an example, force sensitive resistors may be printed on a foil using screen printing techniques. Advantageously, they are based on carbon fillers, such as graphene nanoplatelets or carbon nanotubes, as such sensors show very little hysteresis. Thus, the array of force sensitive resistors screen printed on a first (plastic) foil may be connected along columns and rows by conductive comb electrodes screen printed on a second (plastic) foil, thus forming a network of voltage dividers. Each of the columns and rows is powered and controlled separately using an electronic driver so that a measuring signal can be obtained from each individual force sensitive resistor. Typically, the resistors vary in resistance in a range of 300 to 3500 Ohm, reducing their resistance with increasing force exerted.

In the embodiments shown in **Figures 1A**, **1B**, and **2A**, the force sensitive elements 101, …., 303 are aligned in a direction perpendicular to the top surface 11 and bottom surface 12. In these embodiments each array 100, 200, 300 is arranged as a rectangular matrix. Together they constitute a 3D macro-array having a simple cubic unit cell structure. In the embodiment shown in **Figure 2B**, the force sensitive elements of the three arrays constitute a 3D macro-array having a body-centered unit cell structure. These configurations allow a simple even distribution of the force sensitive elements throughout slab 10 for establishing the force distribution inside the robot skin exerted by an object.

If an external force F exerted by an object is applied on the tactile sensor 1 at an angle *alpha* (α) with respect to the normal to the top surface 11 (*i.e.* w.r.t. the Z-direction), due to the elastic characteristics of slab 10, first array 100 will be displaced laterally relative to second array 200. As a consequence similar pressures will be measured by force sensitive elements in different relative locations within the first, respectively the second array. Moreover, the direction of lateral displacement (*i.e.* in a plane parallel to slab's 10 top 11 and bottom 12 surfaces or XY-plane), depends on the angle *beta* (β) of the projection of force F on that plane with respect to an X axis. Thus, by mapping which force resistive elements in the different arrays provide a detection signal allows determining not only the magnitude of the force F exerted by the object, but also the direction. By repetitively reading out the measured signals of each force sensitive elements and mapping the correlation between the elements in the top 100, medium 300, and bottom 200 arrays it is even possible to determine an object slips along the robot skin's surface. Thus advantageously, the invention allows providing a feedback signal for controlling the movements of the fingers in a robot's finger gripper system to maintain the object in a dynamic equilibrium, such as the spinning of a pen with the finger tips, or around and between the fingers of a hand.

In the embodiment shown in **Figure 3**, the top array 100 and bottom array 200 are each subdivided in two partitions: partitions 110, and 120 for the top array, and partitions 210, and 220 for the bottom array. A similar partition may be made for the optional third array 300. Advantageously, the first partitions110, 210 are stacked on top of each other, as are the second partitions 1§20, 220. This configuration beneficially allows associating the first partitions 110, 210 with a first phalange of a robot's finger, and the second partitions 120, 220 with a second phalange of that finger. The arrays 100, 200, 300 may be further partitioned to include third or fourth partitions for associating them with a third or fourth phalange. Advantageously, the embodiment allows determining the force F value and direction exerted on the individual phalanges, and hence provides for dynamically controlling the position of the individual phalanges of the robot's fingers. In a more elaborate embodiment, the first, second, third, *etc.* partitions are further subdivided in respective left, middle, and right sub-partitions relative to an axial direction of the robot's finger. These sub-partitions allow controlling the movement of an object between two adjacent fingers of a robot's finger gripper system. Beneficially, the tactile sensor extends as a unitary device over all phalanges of a robot's finger. Moreover, the tactile sensor 1 is configured in a three dimensional shape. In particular, the tactile sensor 1 is curved around an axis A running parallel to a lengthwise direction of a robot's finger, so that the at least a force exerted on the finger can be detected in at least a part, respectively the whole of the finger's circumference.

For allowing a robot's finger to curl-up by moving its phalanges relative to each other without detrimental effect on the measuring capabilities of the unitary tactile sensor 1, the latter comprises a groove 20 in the top surface 11 of slab 10. Beneficially, as shown in **Figure 4**, groove 20 is oriented at approximately right angles with respect to a lengthwise direction of the robot's finger. Groove 20 prevents the formation of a bulge of elastomeric slab material adjacent to the joint connecting the finger's phalanges. Such a bulge in the elastomeric material would displaces the force sensitive elements in the top 100, middle 300, and bottom 200 arrays relative to each other, especially those elements near the joint. Such a displacement would have a detrimental effect on the accuracy of an object's position and orientation measurement. For this reason, the groove is preferentially positioned between the first partitions 110, 210 and the second partitions 120, 220, respectively associated with a first and second phalange.

Although the invention has been elucidated with reference to the embodiments described above, it will be evident that alternative embodiments may be used to achieve the same objective. The scope of the invention is therefore not limited to the embodiments described above.

As an example, while the force sensitive elements in the respective arrays have been described above by a rectangular matrix, there is no need for such a limitation. The invention may be realized by implementing any regular or irregular array. For example, from observing humans manipulating objects it becomes evident that these objects are preferentially operated by specific finger parts, while other finger parts hardly come into contact with the object. Hence, to balance between accuracy in determining the force distribution and economizing on data processing, the density and layout of the force sensitive elements in the arrays may vary in dependence of the location on the finger.

Patent claims

1. A tactile sensor (1) comprising:
   - a slab (10) of elastomeric material having a top surface (11) and a bottom surface (12);
   - a first array (100) of force sensitive elements (101, 102, 103) embedded in the slab adjacent to the top surface;
   - a second array (200) of force sensitive elements (201, 202, 203) embedded in the slab adjacent to the bottom surface

2. A tactile sensor (1) according to claim 1, further comprising a third array (300) of force sensitive elements (301, 302, 303) embedded in the slab (10) intermediate between the first (100) and second (200) arrays.

3. A tactile sensor (1) according to claims 1 or 2, wherein the force sensitive elements (101, 102, 103, 201, 202, 203, 301, 302, 303) of the arrays (100, 200, 300) are aligned in a direction perpendicular to the top surface (11).

4. A tactile sensor (1) according to claim 2, wherein the force sensitive elements (101, 102, 103, 201, 202, 203) of the first and second arrays (100, 200) are aligned in a direction perpendicular to the top surface (12) while the force sensitive elements (301, 302, 303) of the third array (300) are dis-aligned.

5. A tactile sensor (1) according to any of the previous claims, wherein the arrays (100, 200, 300) are each subdivided in a first partition (110, 210) and a second partition (120, 220).

6. A tactile sensor (1) according to claim 5, further comprising a groove (20) in the top surface (11) of the slab (10).

7. A tactile sensor (1) according to claim 6, wherein the groove (20) is positioned between the first partitions (110, 210) and the second partitions (210, 220).

8. A tactile sensor (1) according to any of the previous claims, wherein the slab (10) forms a three-dimensional shape.

9. A tactile sensor (1) according to claim 8, wherein the slab is curved around an axis (A) aligned essentially parallel to the top (11) and bottom (12) surfaces.

10. A tactile sensor (1) according to any of the previous claims, wherein the force sensitive elements (101, ... , 303) are force sensitive resistors.

11. A finger gripper system for a robot comprises a sensor (1) according to any of the claims 1 to 10.

12. A finger gripper system according to claim 11, wherein the finger system comprises a finger having a first phalange and a second phalange connected by a joint allowing the first and second phalanges to move relative to each other, wherein the sensor extends over the first and second phalanges.

13. A finger gripper system according to claim 12, wherein the sensor (1) comprises a groove (20) in the top surface (11) of the slab (10), and the groove is located adjacent to the joint.

14. A finger system according to claim 13, wherein the arrays (100, 200, 300) are each subdivided in a first partition (110, 210) and a second partition (120, 220), and the first partition is associated with the first phalange and the second partition is associated with the second phalange.

15. A robot comprising a finger gripper system according to any of the claims 11 to 14.

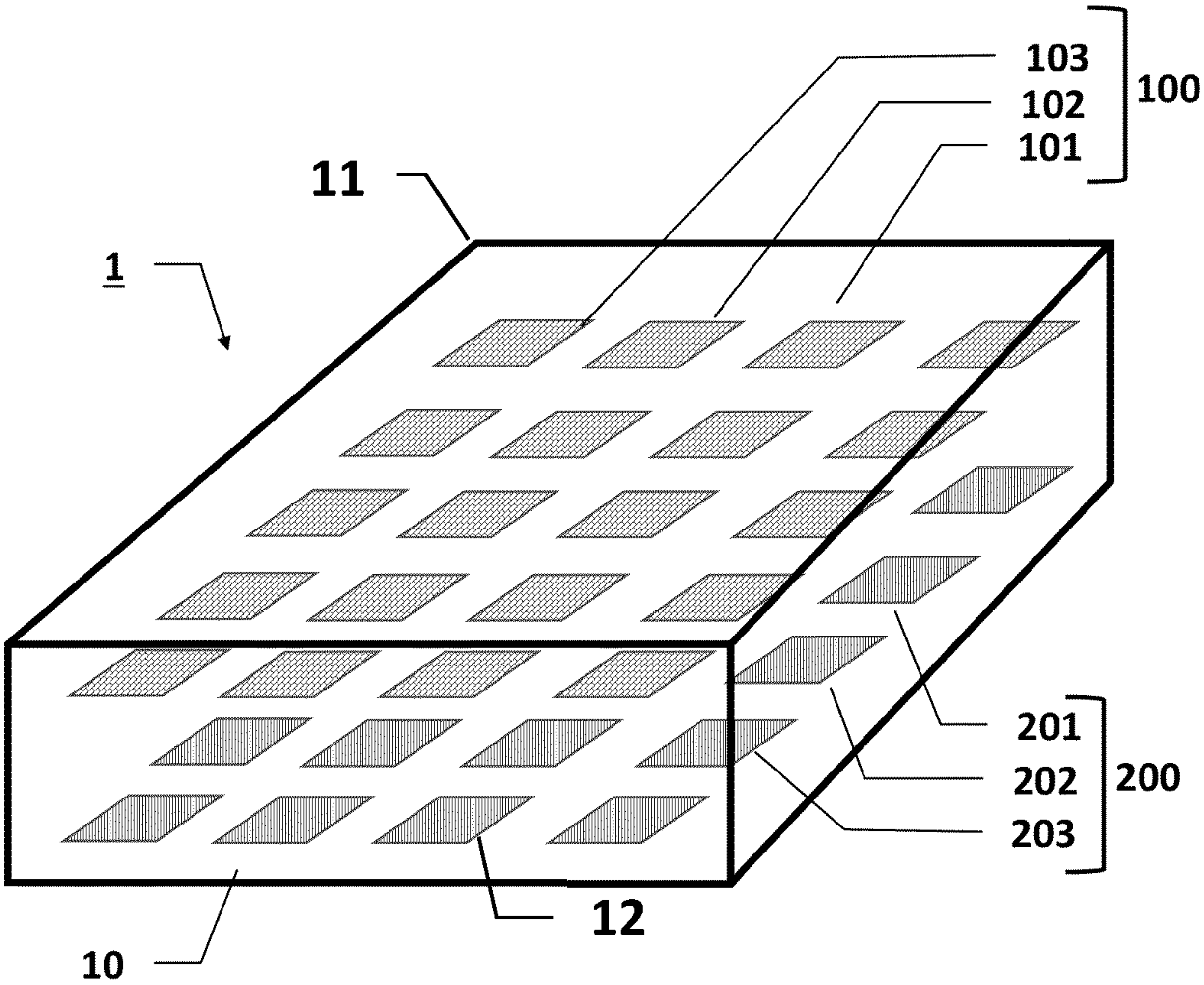
103
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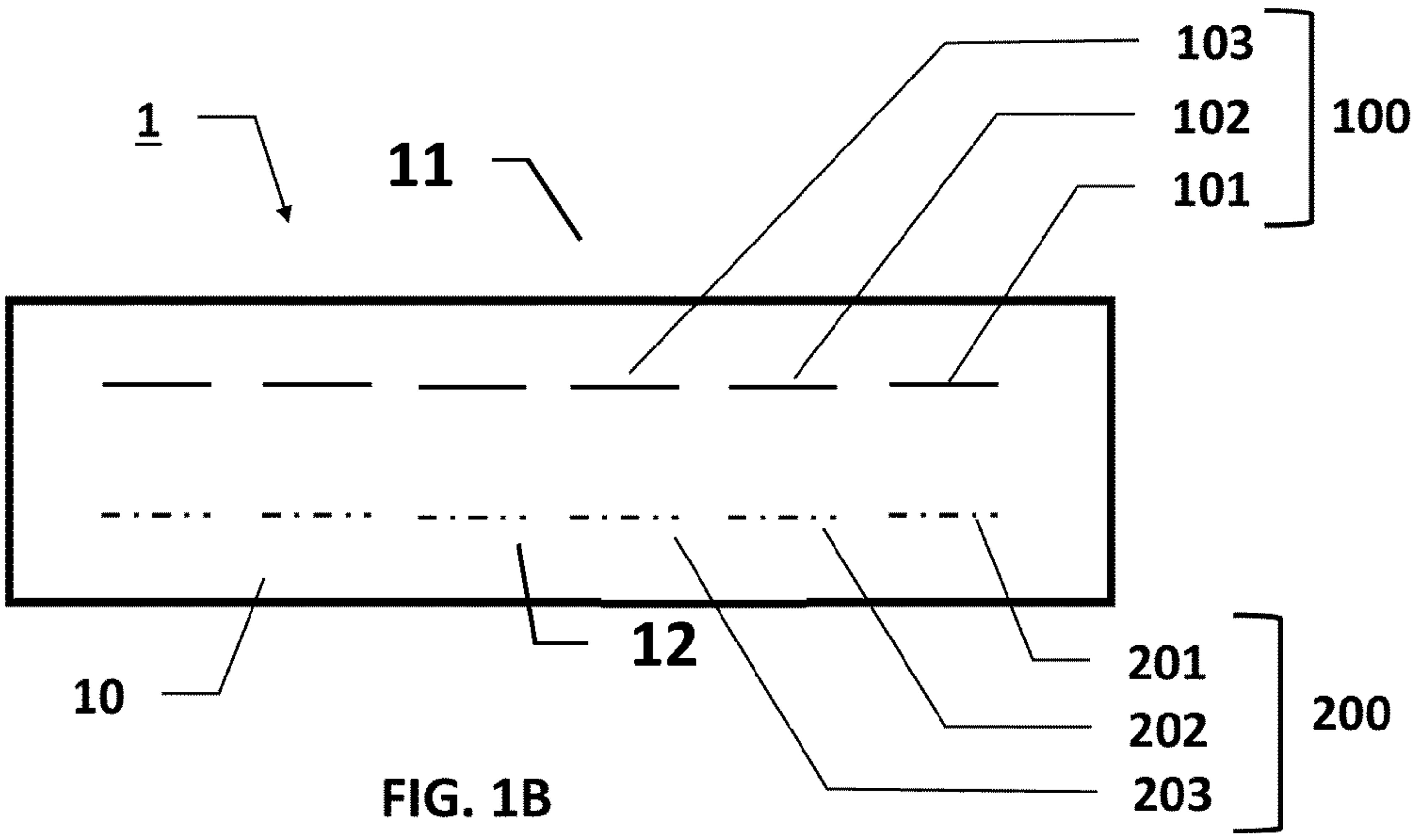
FIG. 1A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200
203

FIG. 1B

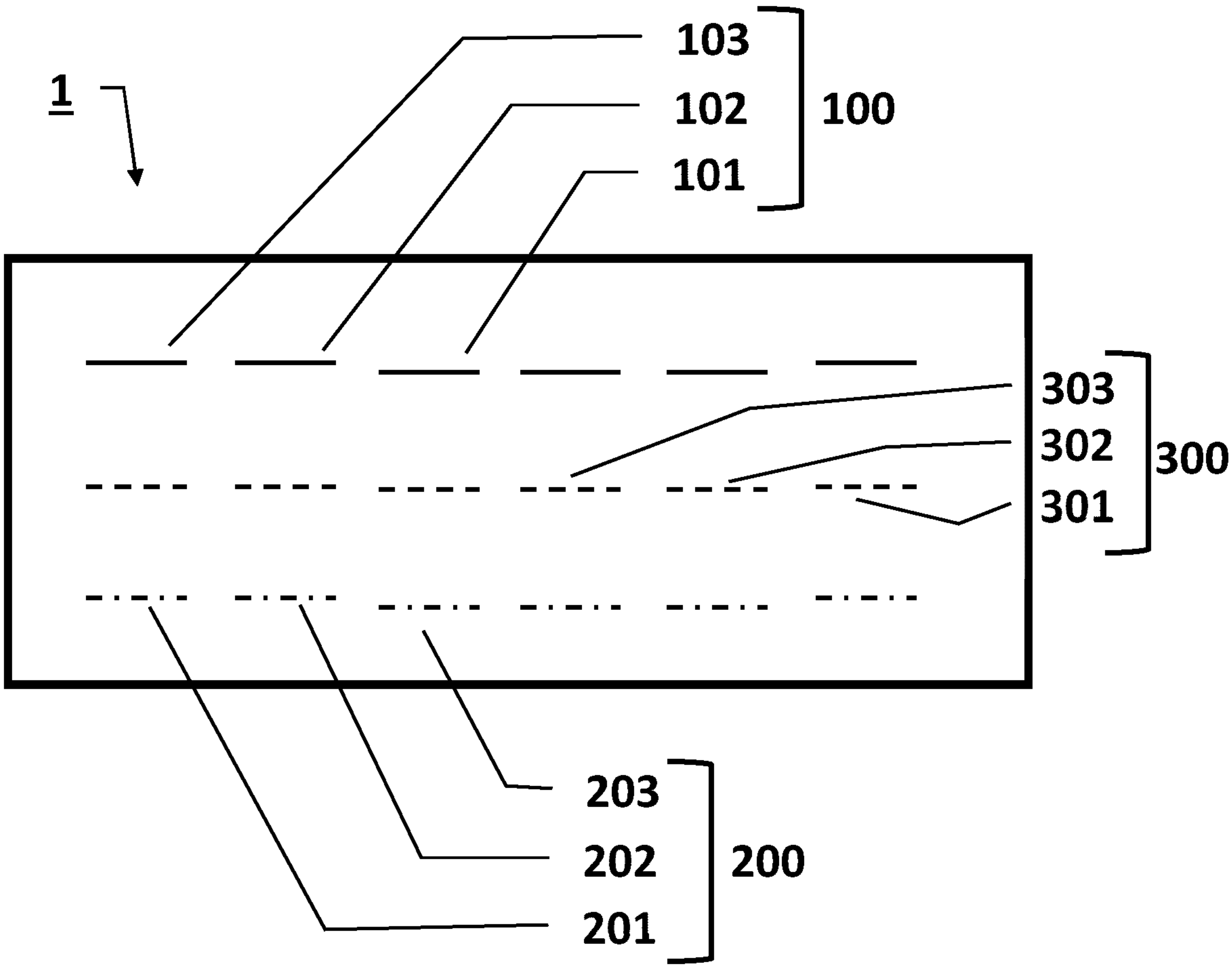


FIG. 2A

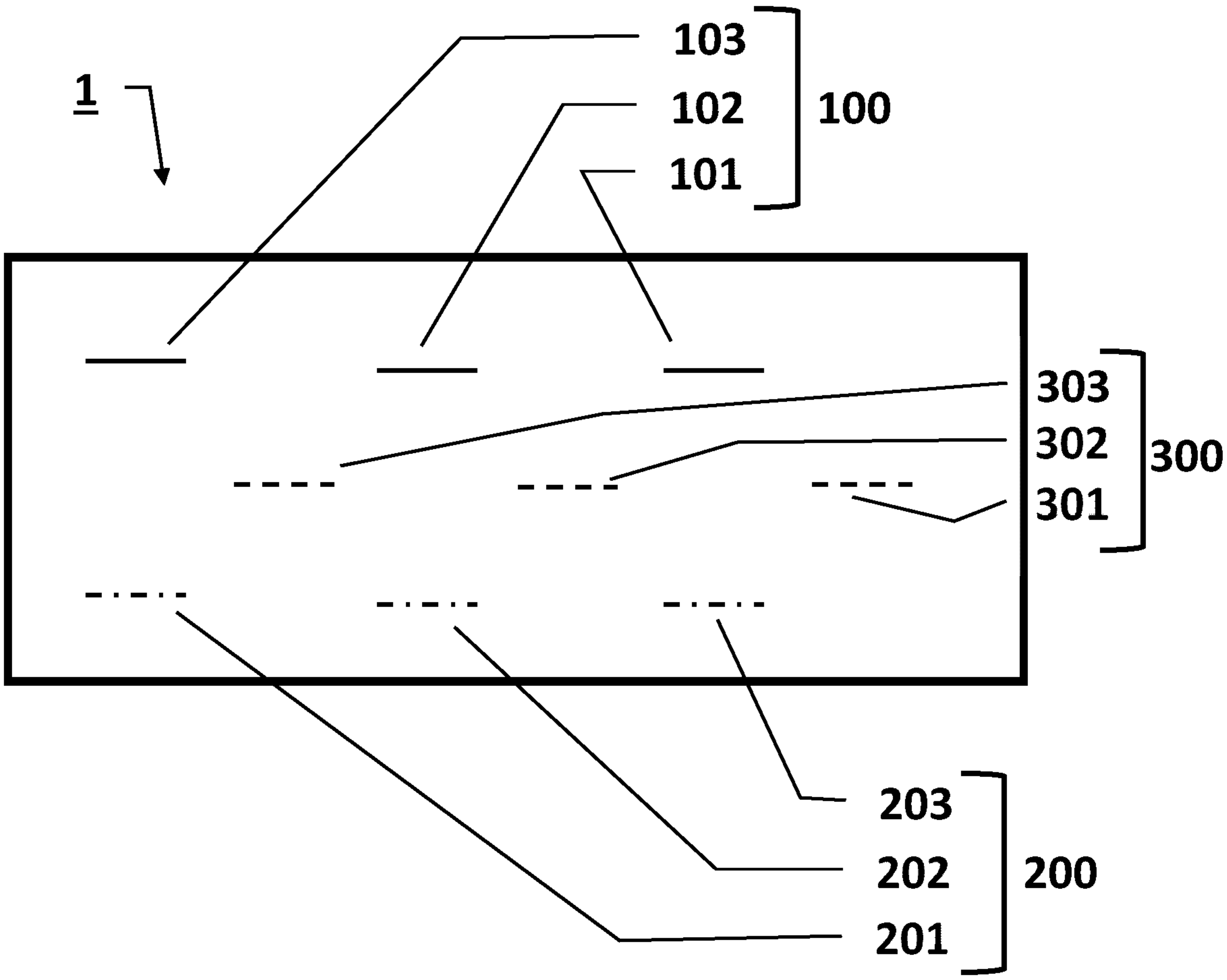


FIG. 2B

FIG. 3

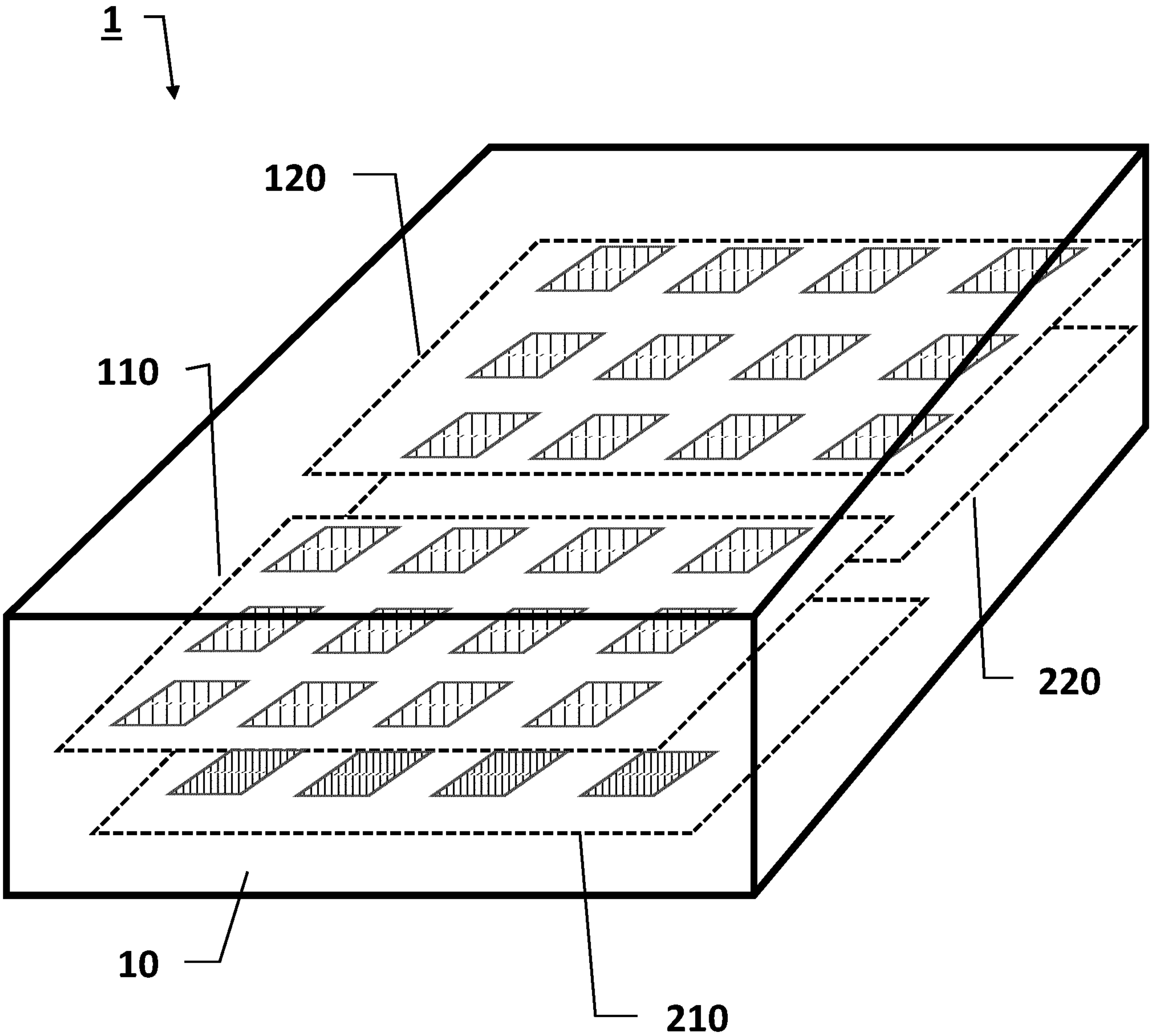
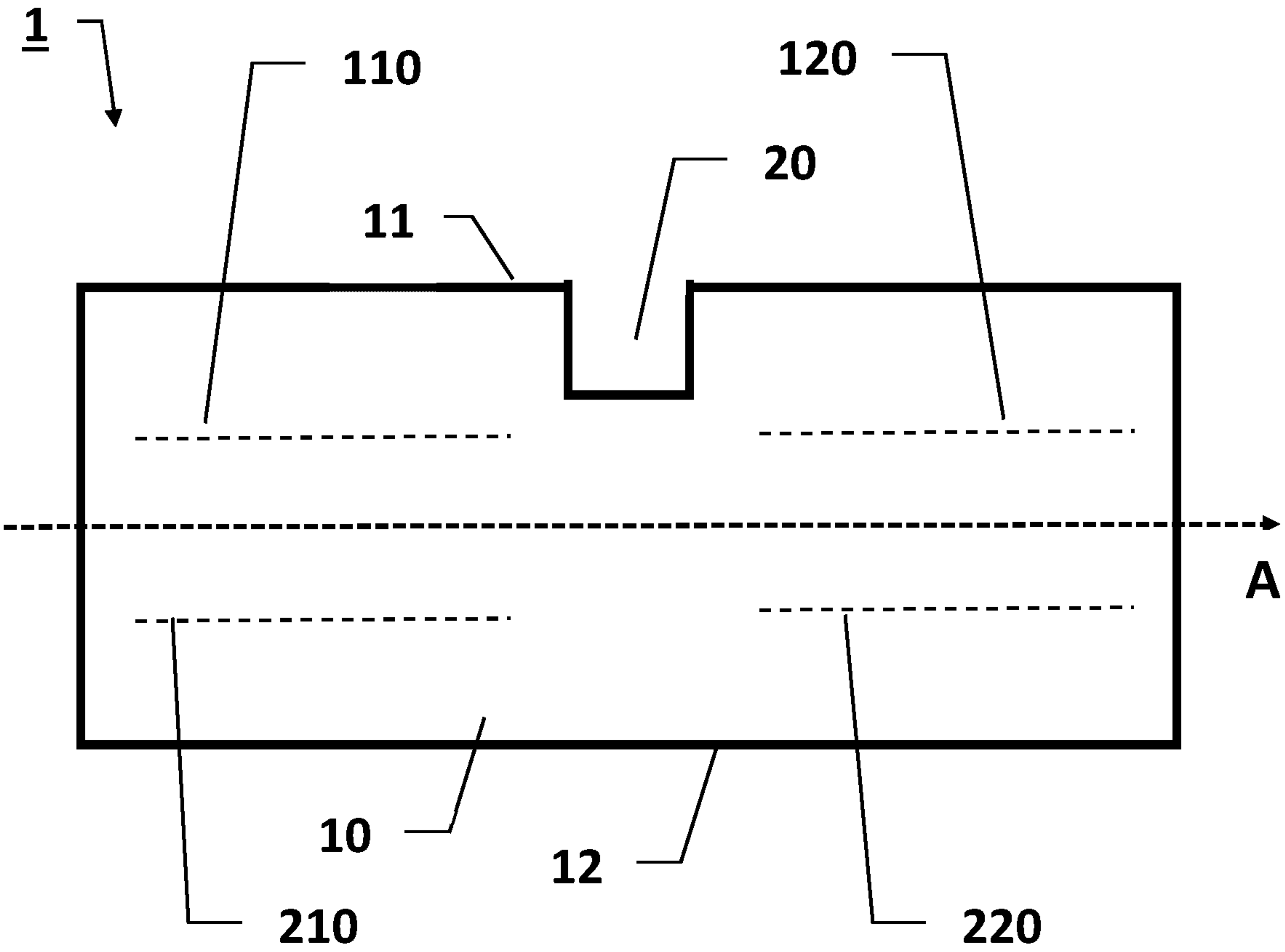


FIG. 4



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/081002

A. CLASSIFICATION OF SUBJECT MATTER
INV. B25J13/08 B25J15/00 G01L5/22
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)
B25J G01L

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	EP 2 060 893 A1 (NAT INST OF ADVANCED IND SCIEN [JP]; UNIV TOKYO [JP]) 20 May 2009 (2009-05-20)	1-4, 8-11,15
Y	paragraph [0047] - paragraph [0049]; figures 1,4,6 paragraph [0207] paragraph [0049] paragraph [0001] -----	5-7, 12-14
X	US 2018/238716 A1 (MADDEN JOHN D W [CA] ET AL) 23 August 2018 (2018-08-23)	1,3
A	claim 1; figures 1,2 paragraph [0070] -----	2,4-15
Y	US 2015/343647 A1 (GARCIA PABLO E [US] ET AL) 3 December 2015 (2015-12-03)	5-7, 12-14
A	figures 32,33 paragraph [0095] - paragraph [0096] -----	1-4, 8-11,15
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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22 January 2021	02/02/2021

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1

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/081002

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 7 420 155 B2 (TOUDAI TLO LTD [JP]) 2 September 2008 (2008-09-02) abstract; figures 1-4 -----	1-15
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