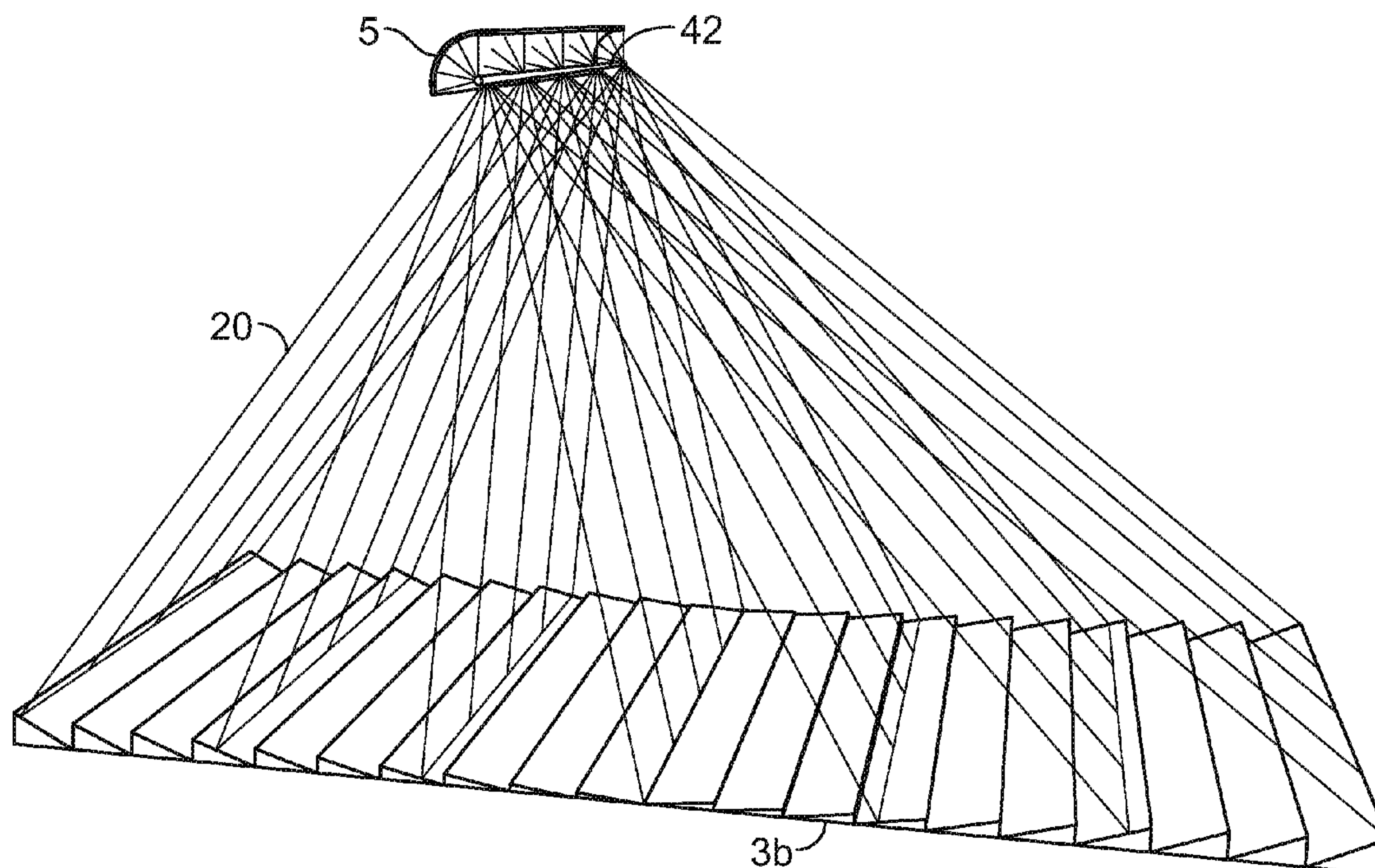


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(19) **United States**(12) **Patent Application Publication**
Reif et al.(10) **Pub. No.: US 2011/0067688 A1**(43) **Pub. Date: Mar. 24, 2011**(54) **SOLAR CONCENTRATOR SYSTEM FOR
SOLAR ENERGY PLANTS****Publication Classification**(75) Inventors: **John H. Reif**, Durham, NC (US);
Katie L. Reif, Durham, NC (US)(73) Assignee: **EAGLE EYE, INC.**, Durham, NC
(US)(21) Appl. No.: **12/889,313**(22) Filed: **Sep. 23, 2010****Related U.S. Application Data**(60) Provisional application No. 61/245,250, filed on Sep.
23, 2009.(51) **Int. Cl.****F24J 2/18** (2006.01)**F24J 2/38** (2006.01)(52) **U.S. Cl.** **126/600**; 126/685; 126/692(57) **ABSTRACT**

Certain embodiments make use of an array of passive primary concentrators positioned on the ground that provide primary concentrated solar radiation from below to an array of tracking secondary concentrators. The secondary concentrators further concentrate the solar radiation to one or more centralized receivers. The solar concentrator system may include apparatus for collection of solar radiation, concentration, and the absorbance of the concentrated solar energy. Some embodiments of the solar concentrator system include a large field of passive horizontal primary concentrators, overhead tracking secondary concentrators, and one or more receivers, which convert solar radiation into usable products or energy, such as electricity.



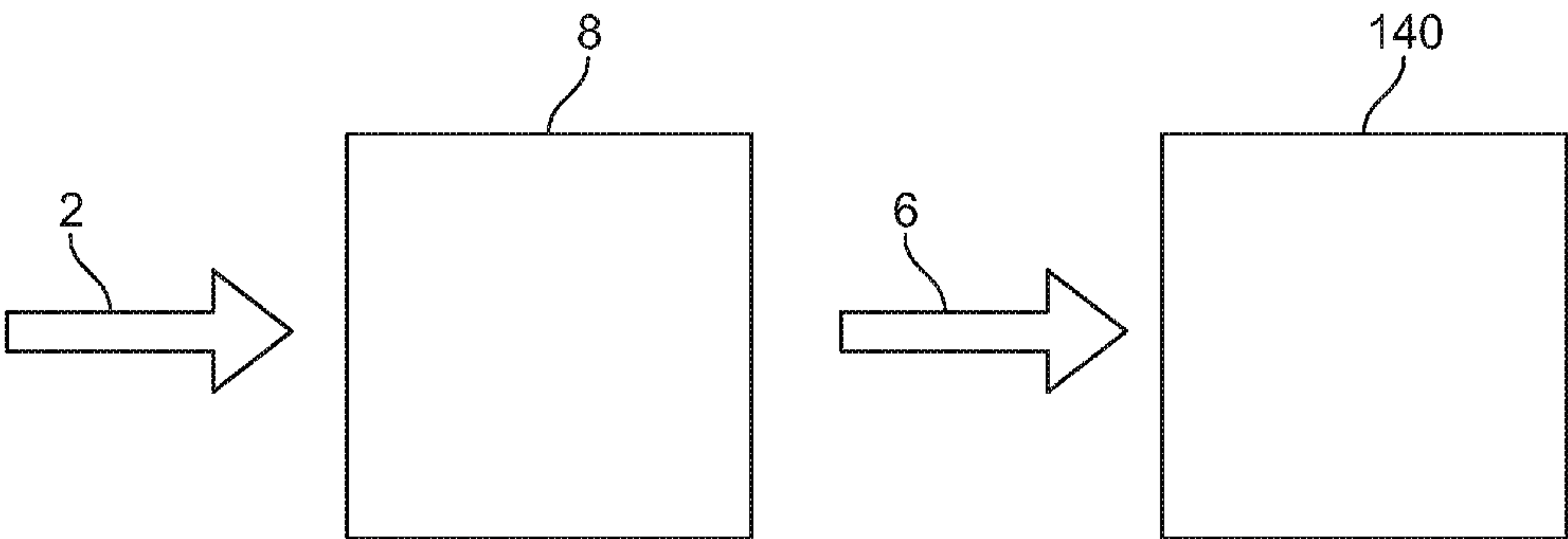


FIG. 1A

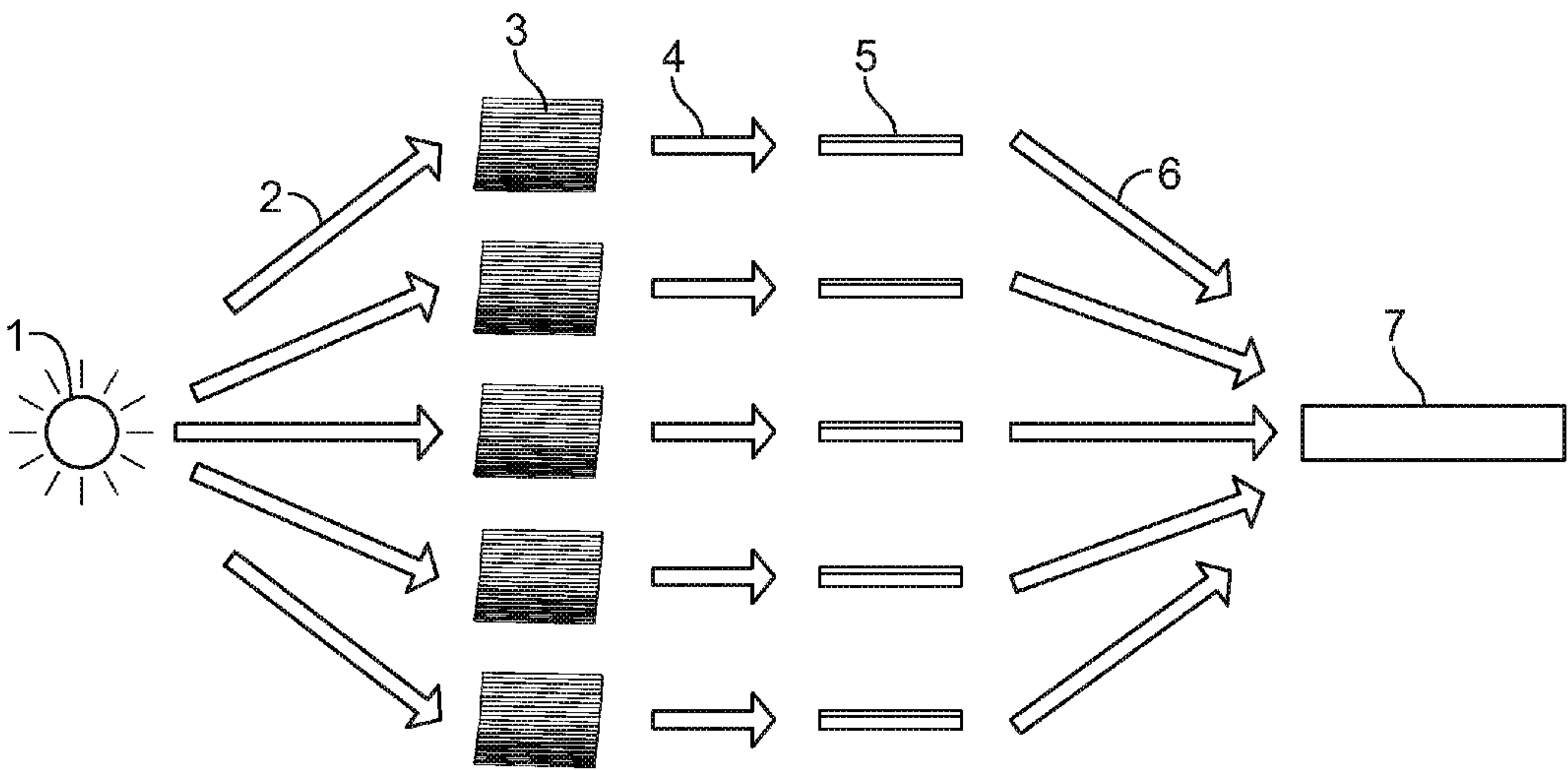


FIG. 1B

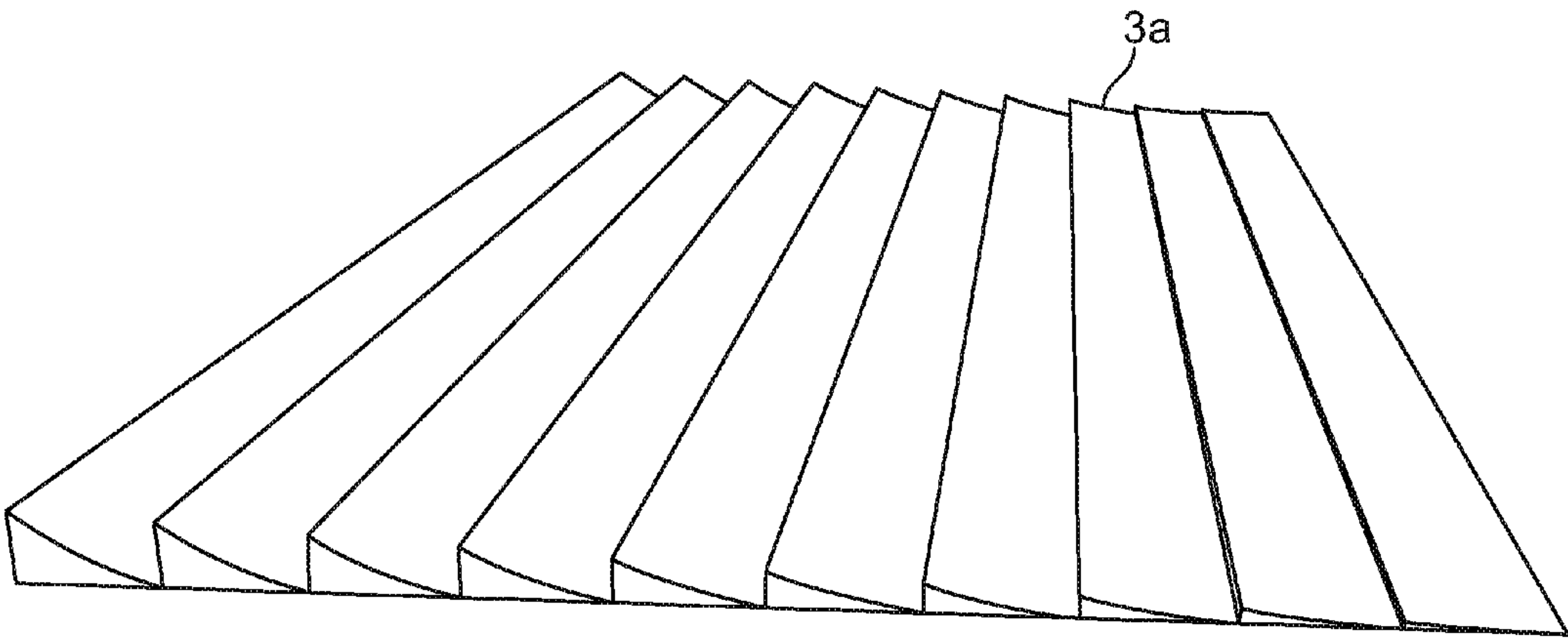


FIG. 2A

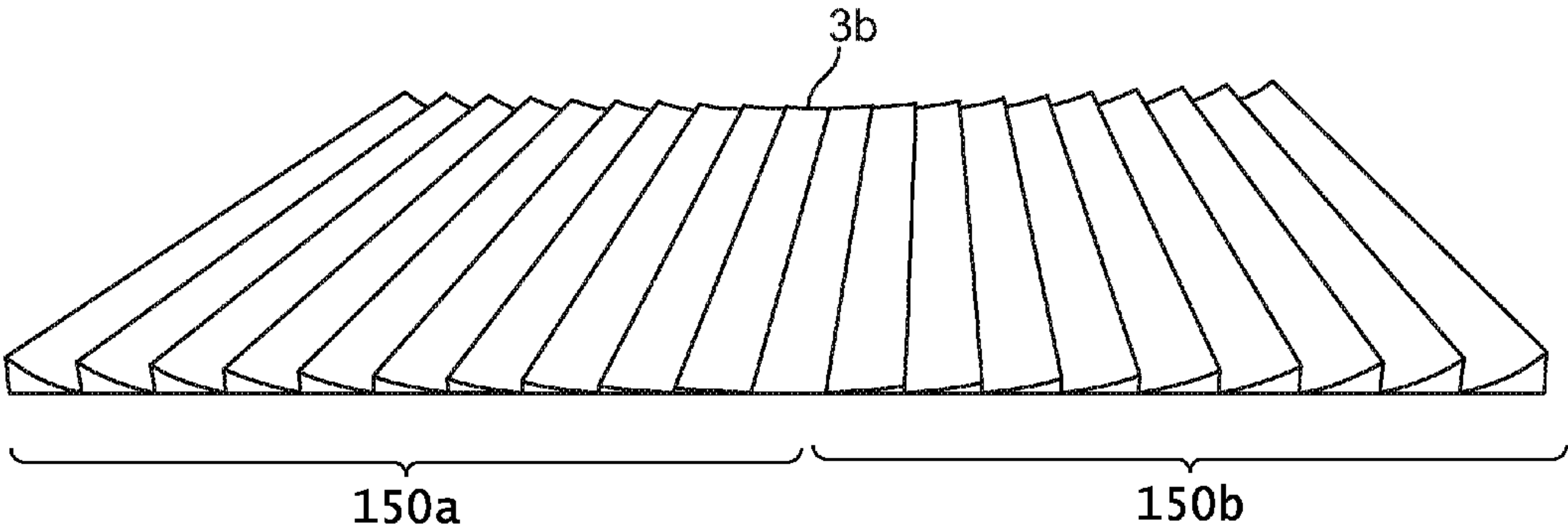


FIG. 2B

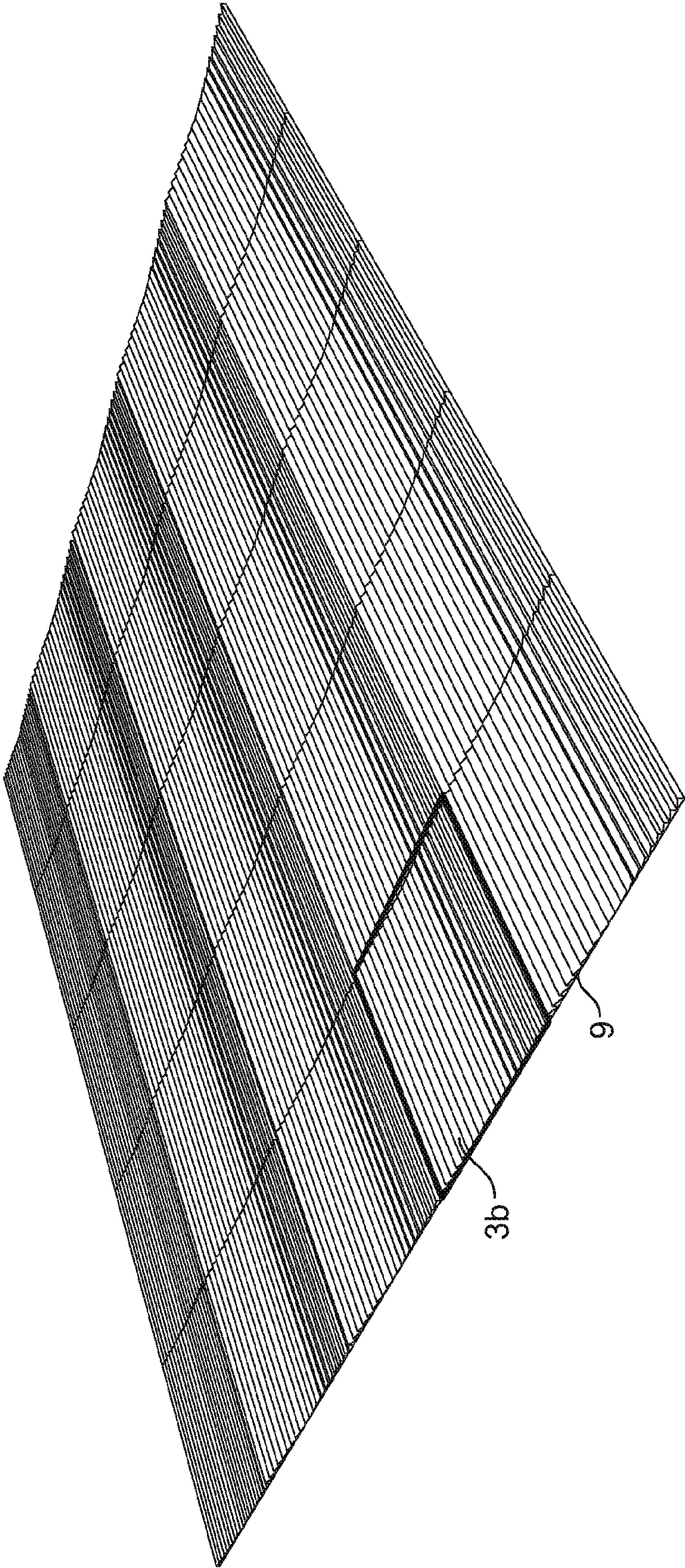


FIG. 3

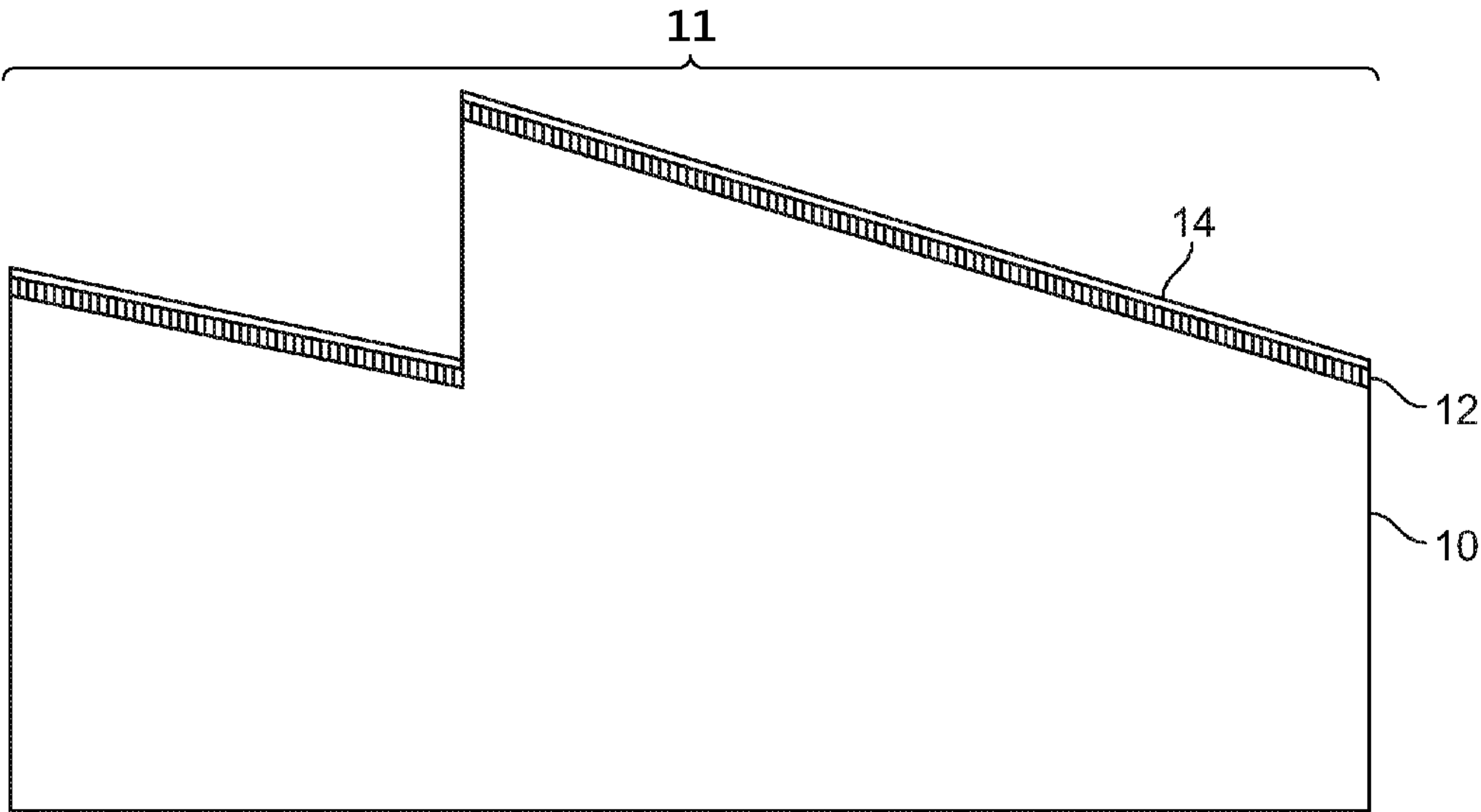


FIG. 4A

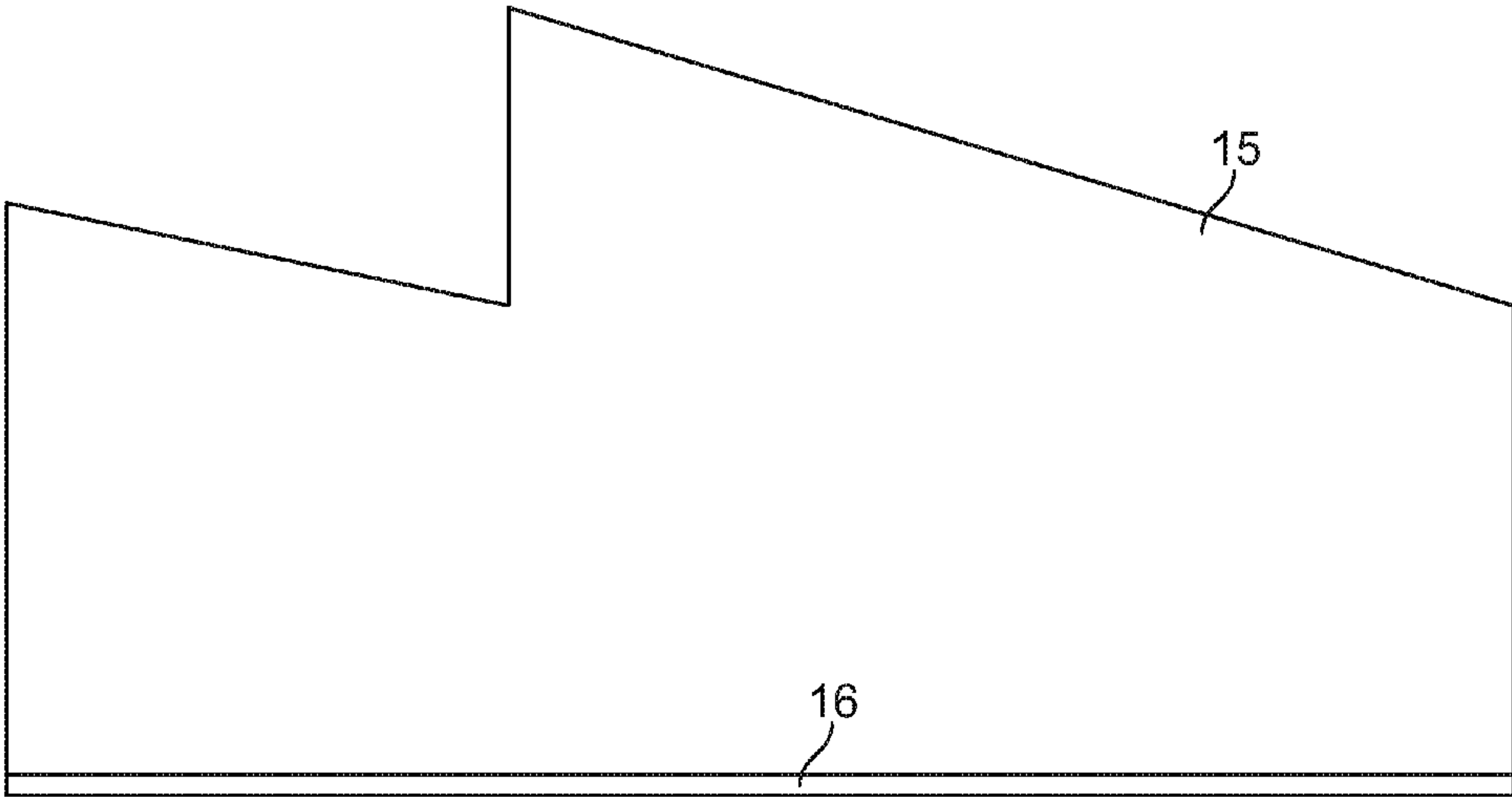


FIG. 4B

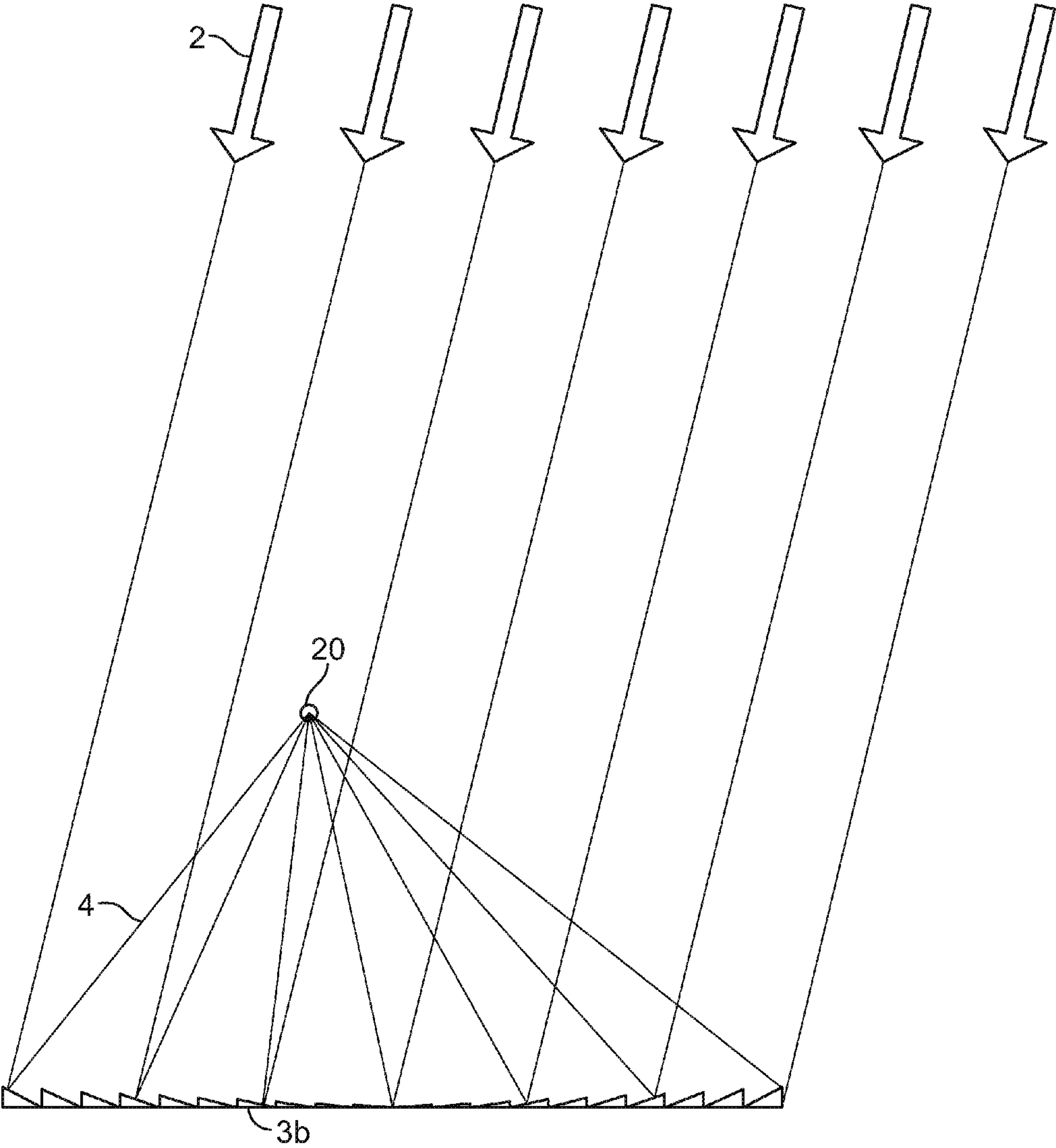


FIG. 5A

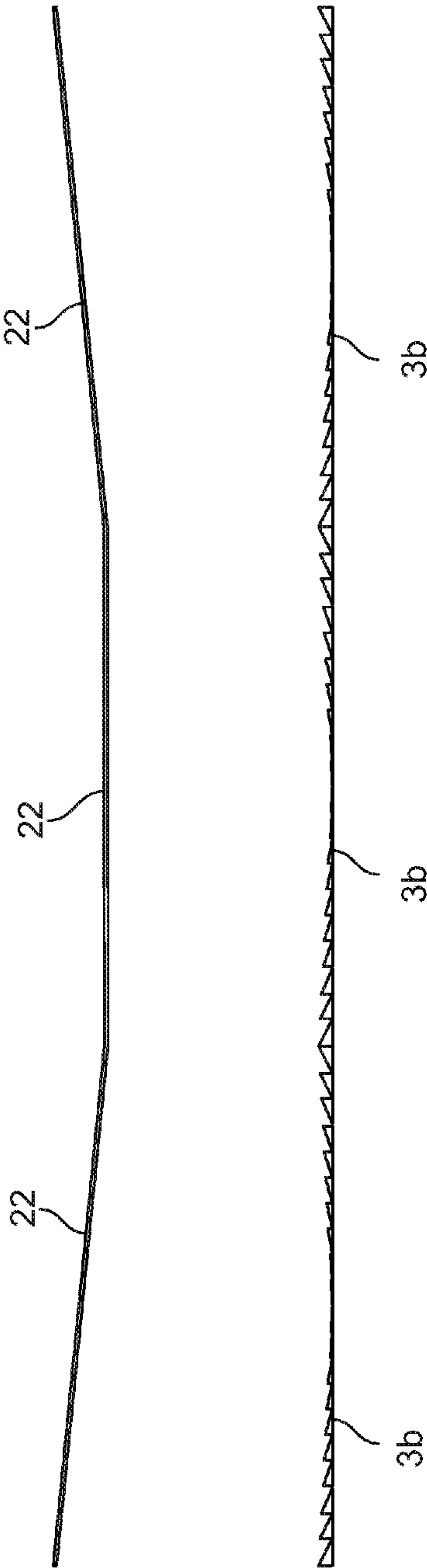


FIG. 5C

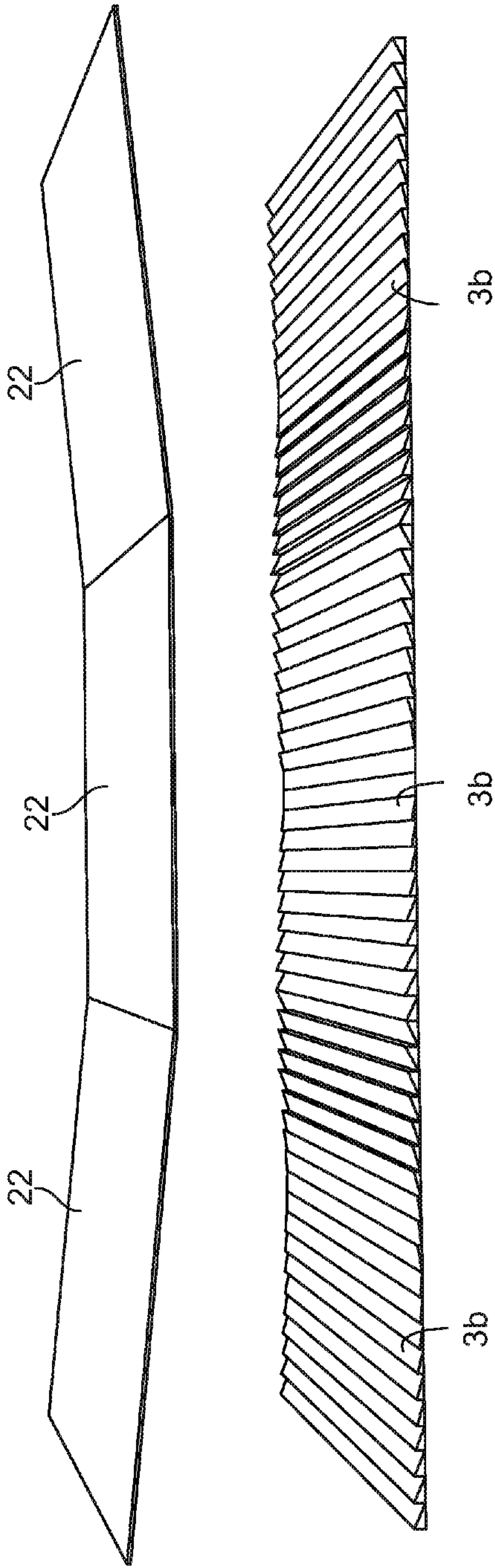
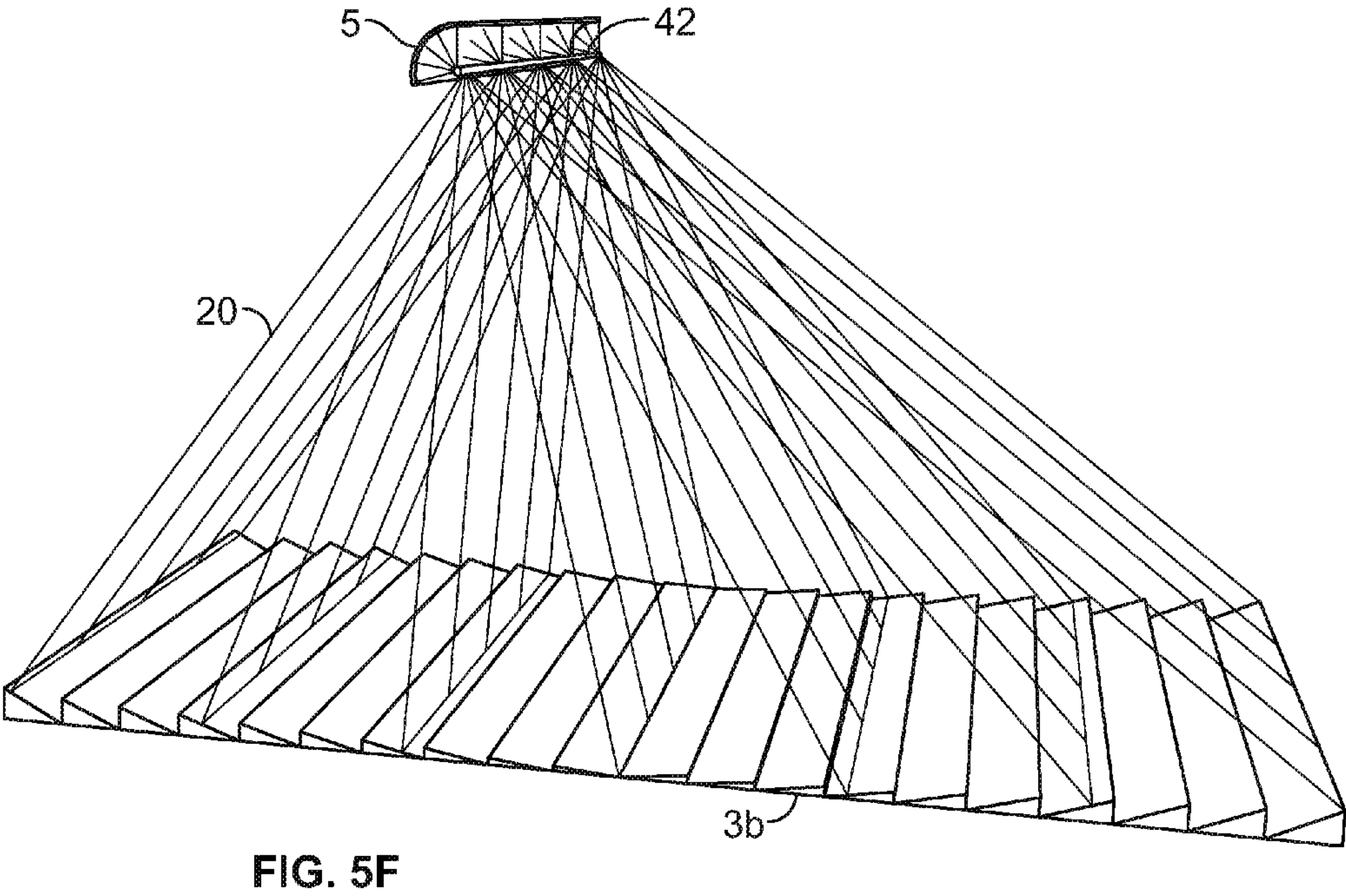
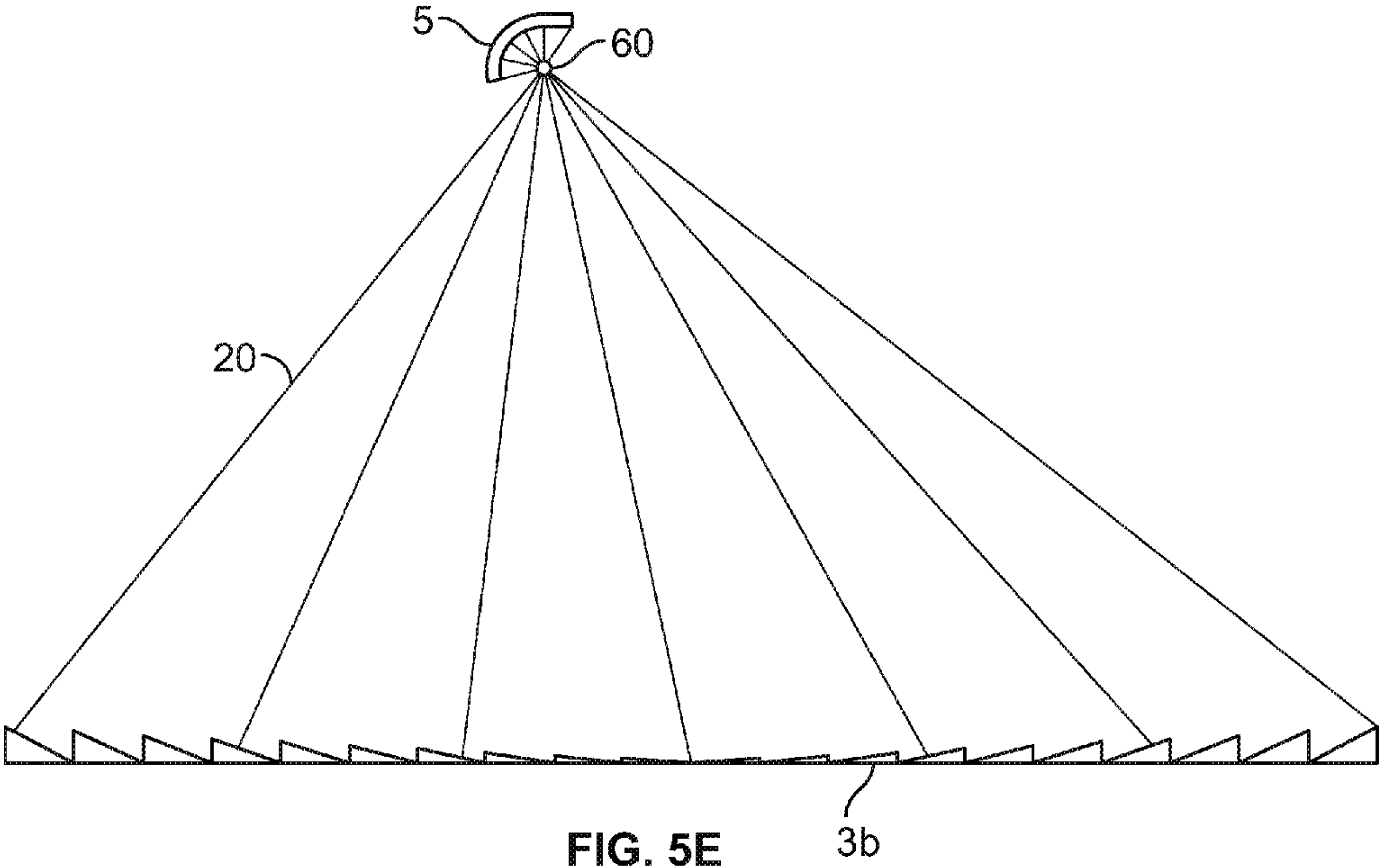


FIG. 5D



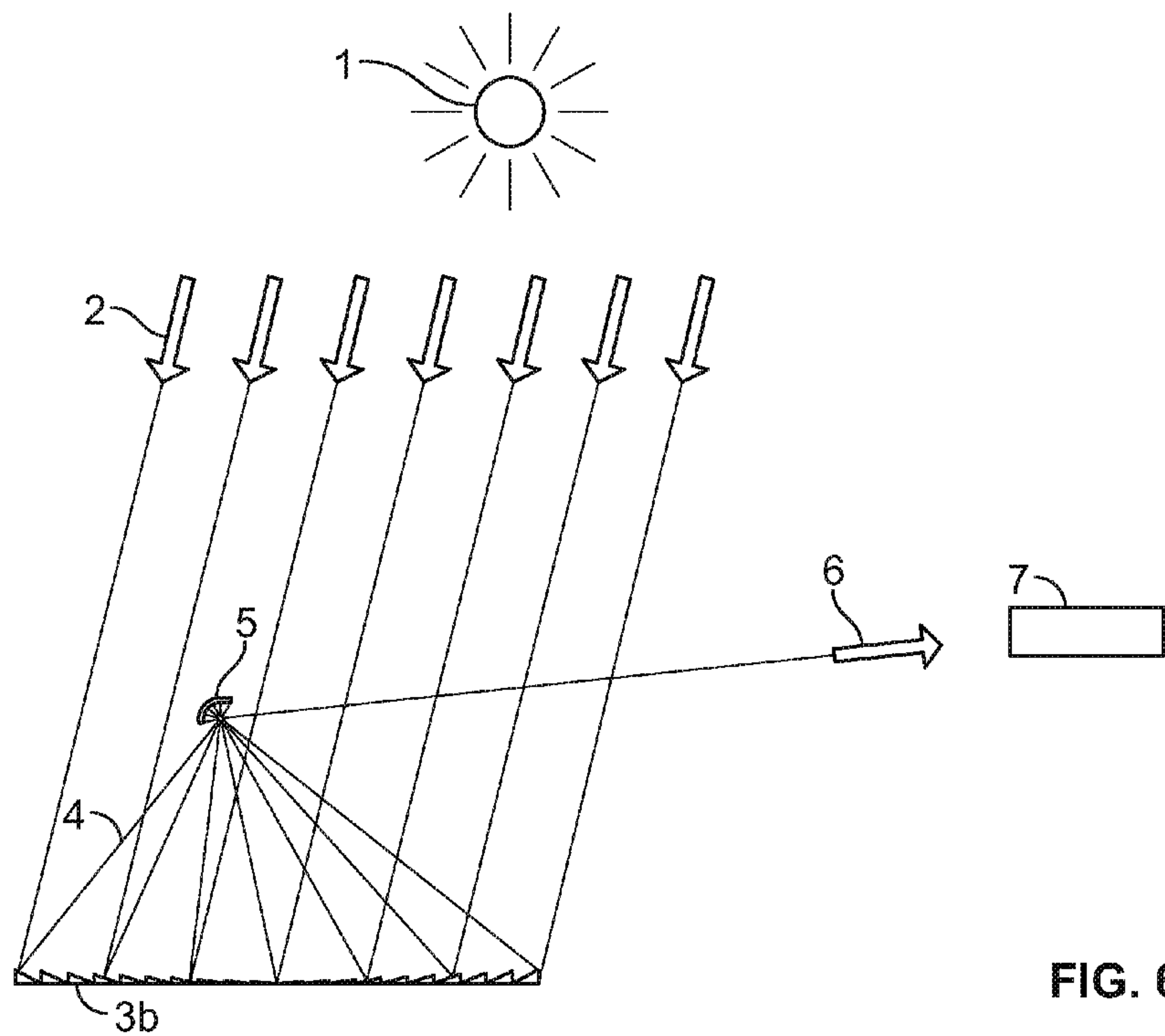


FIG. 6A

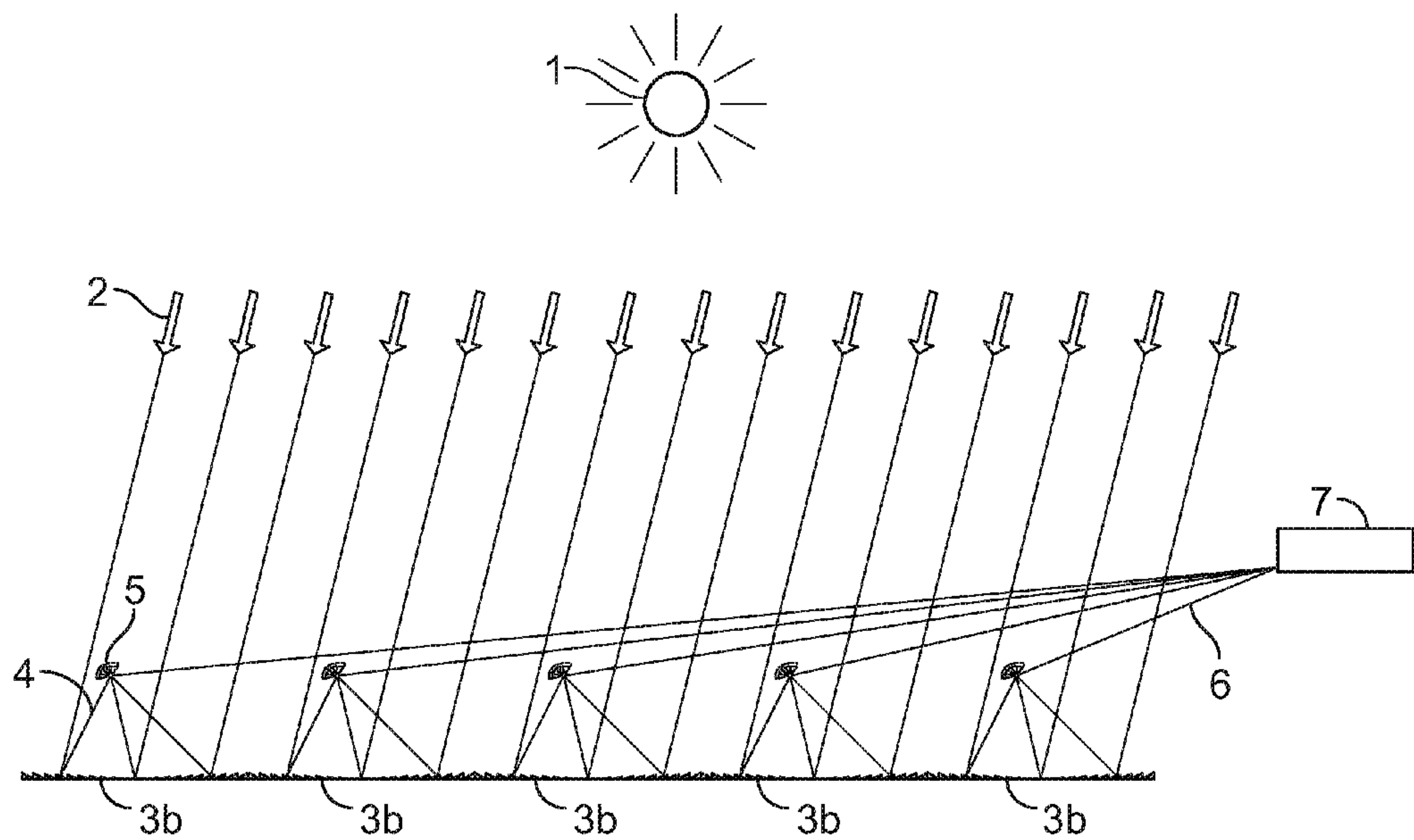


FIG. 6B

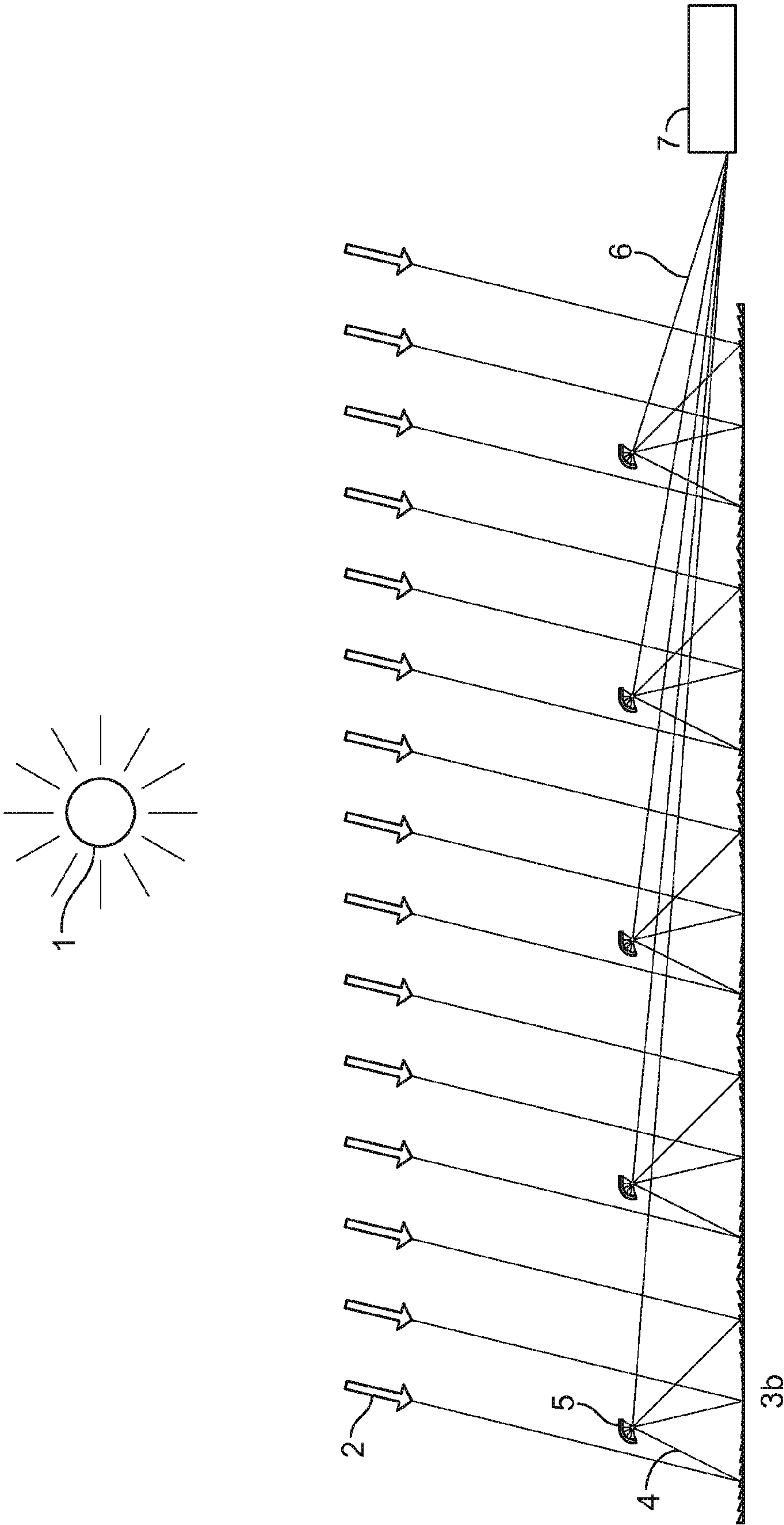


FIG. 6C

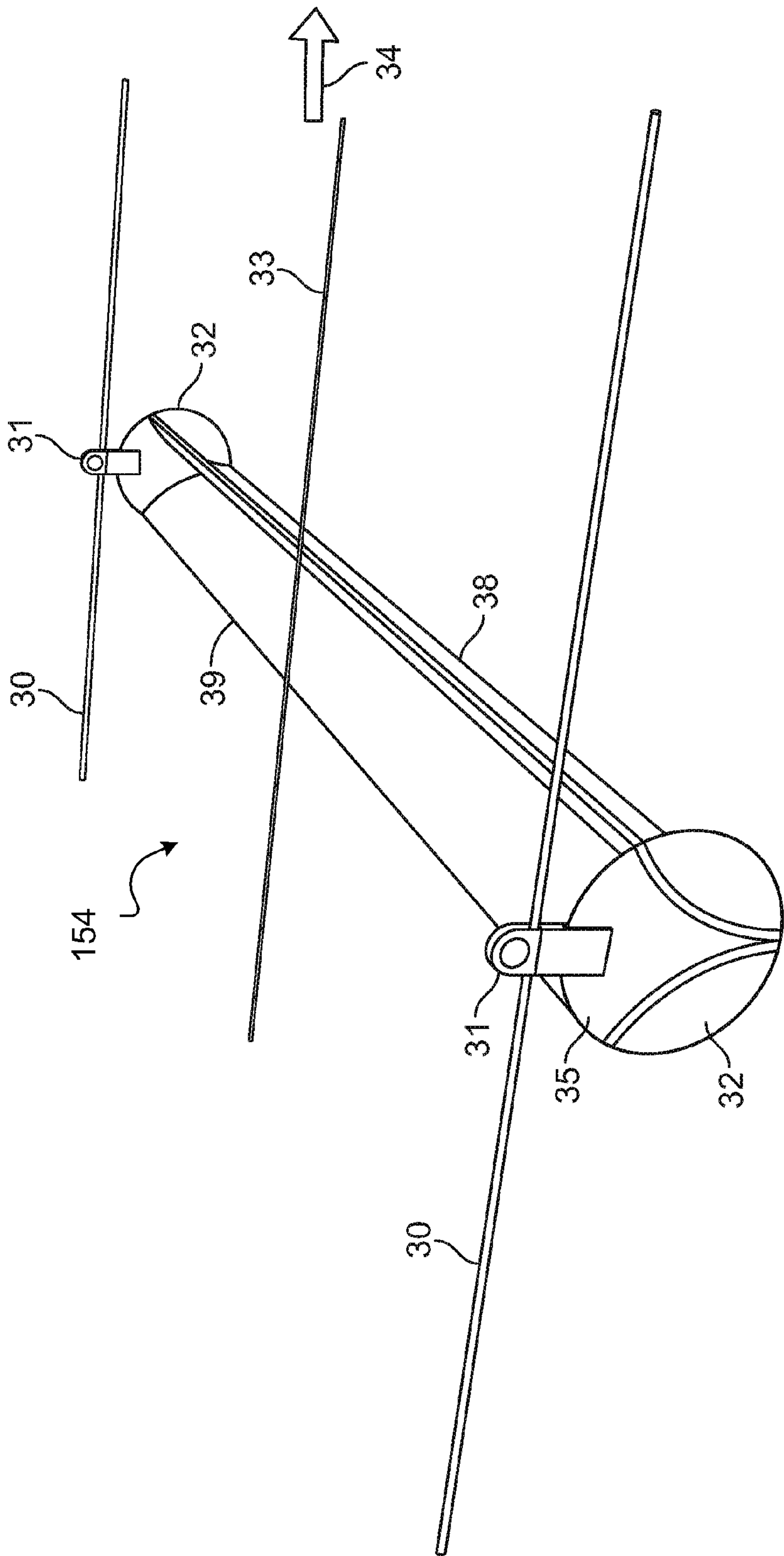


FIG. 7A

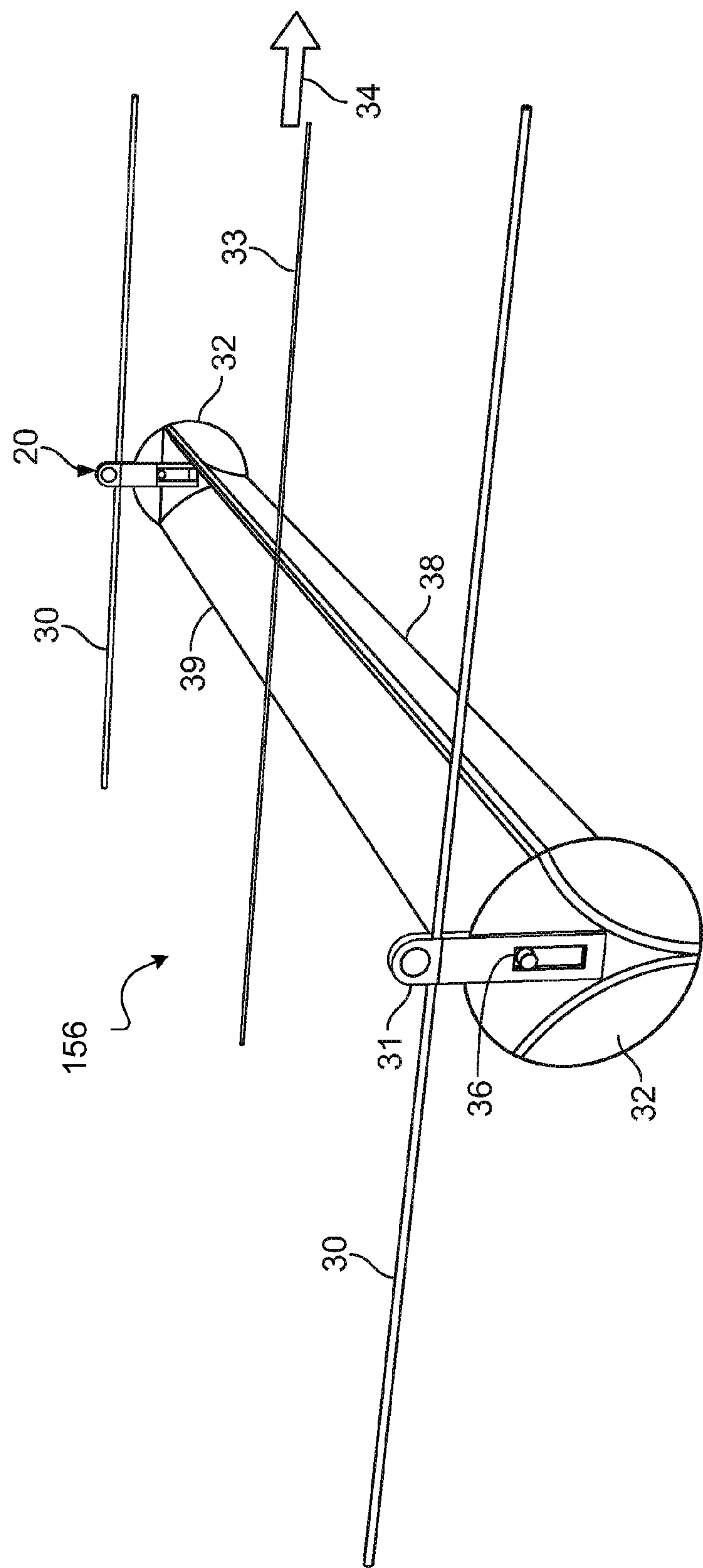


FIG. 7B

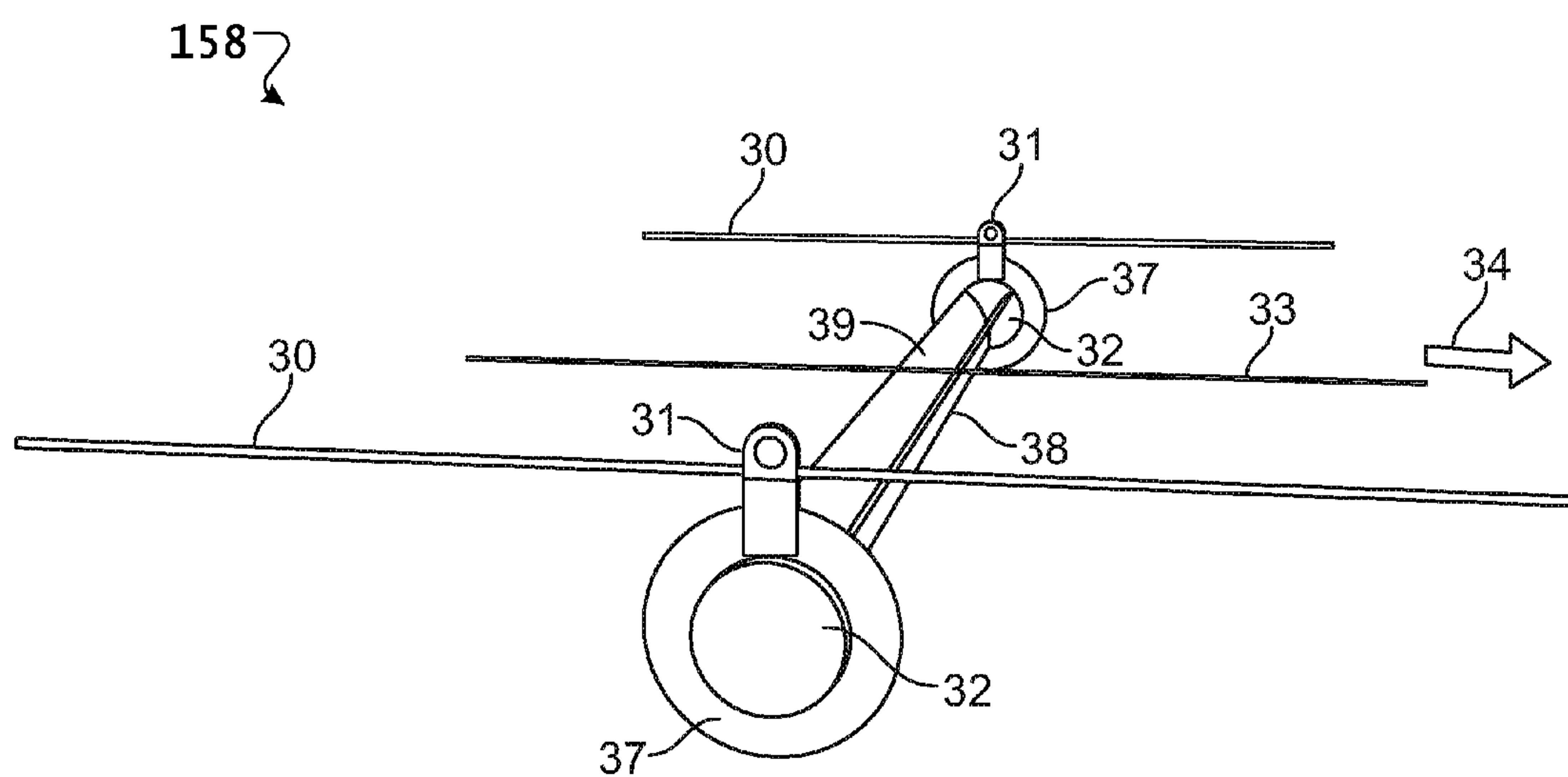


FIG. 7C

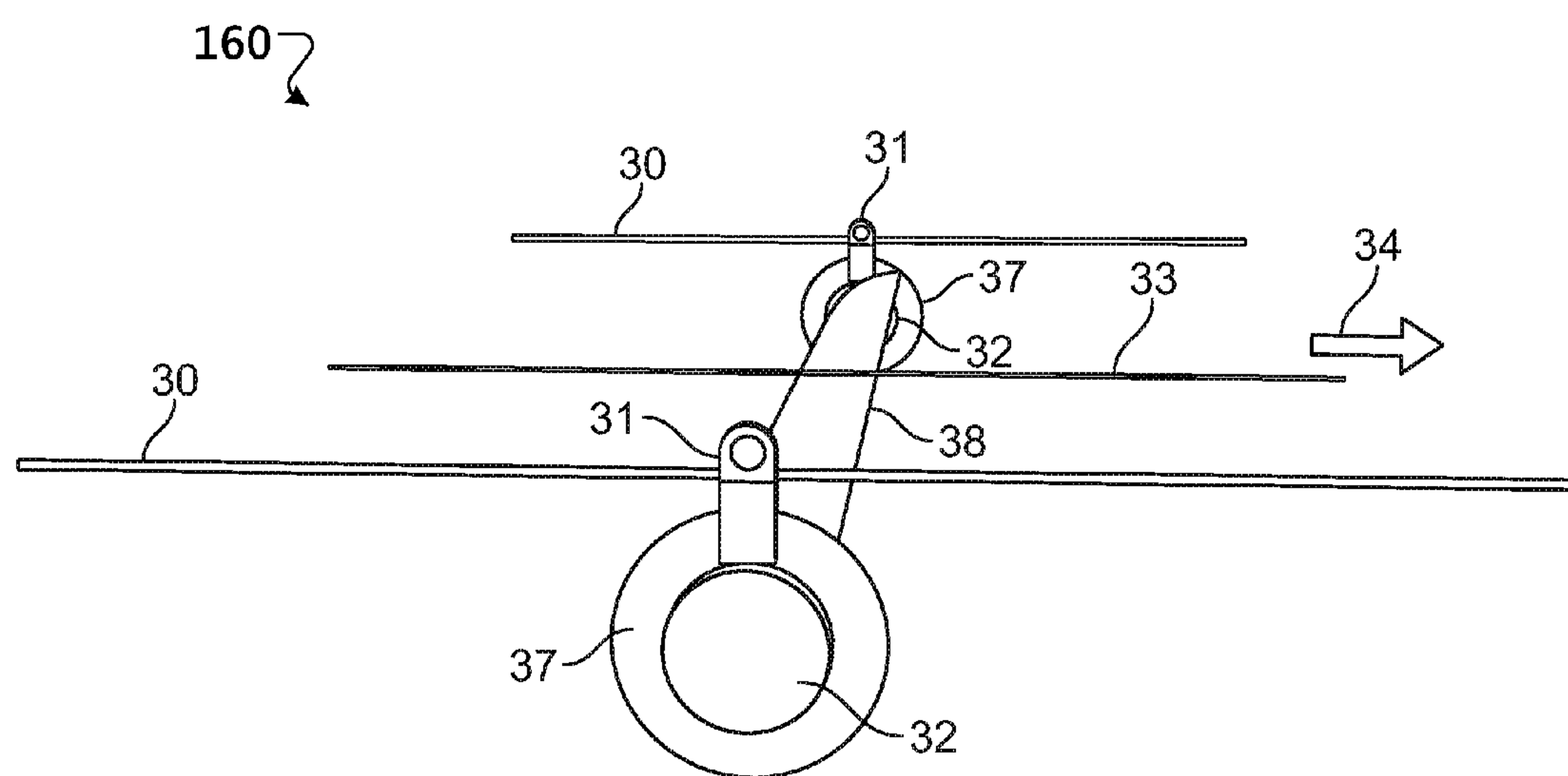


FIG. 7D

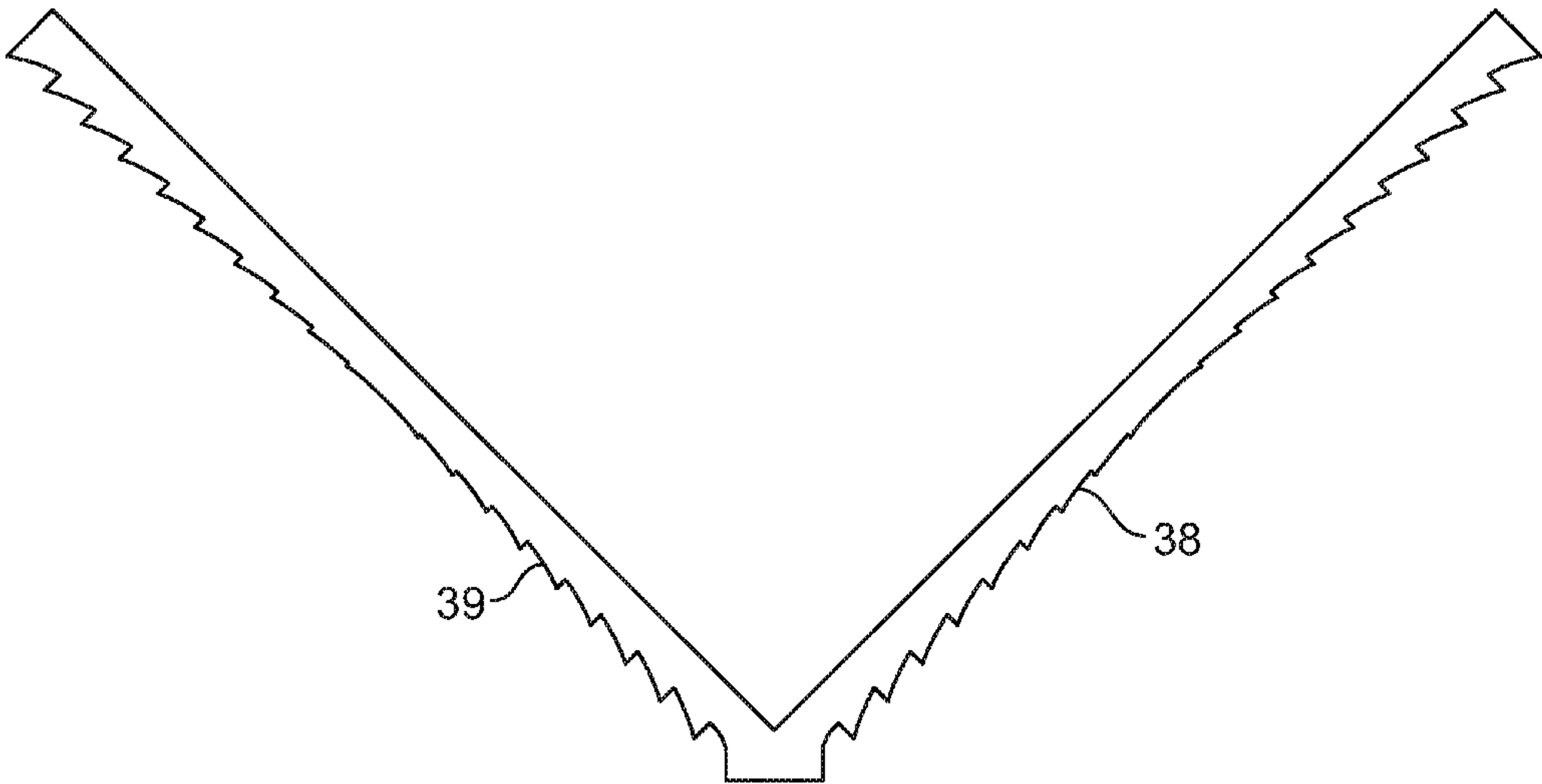


FIG. 7E

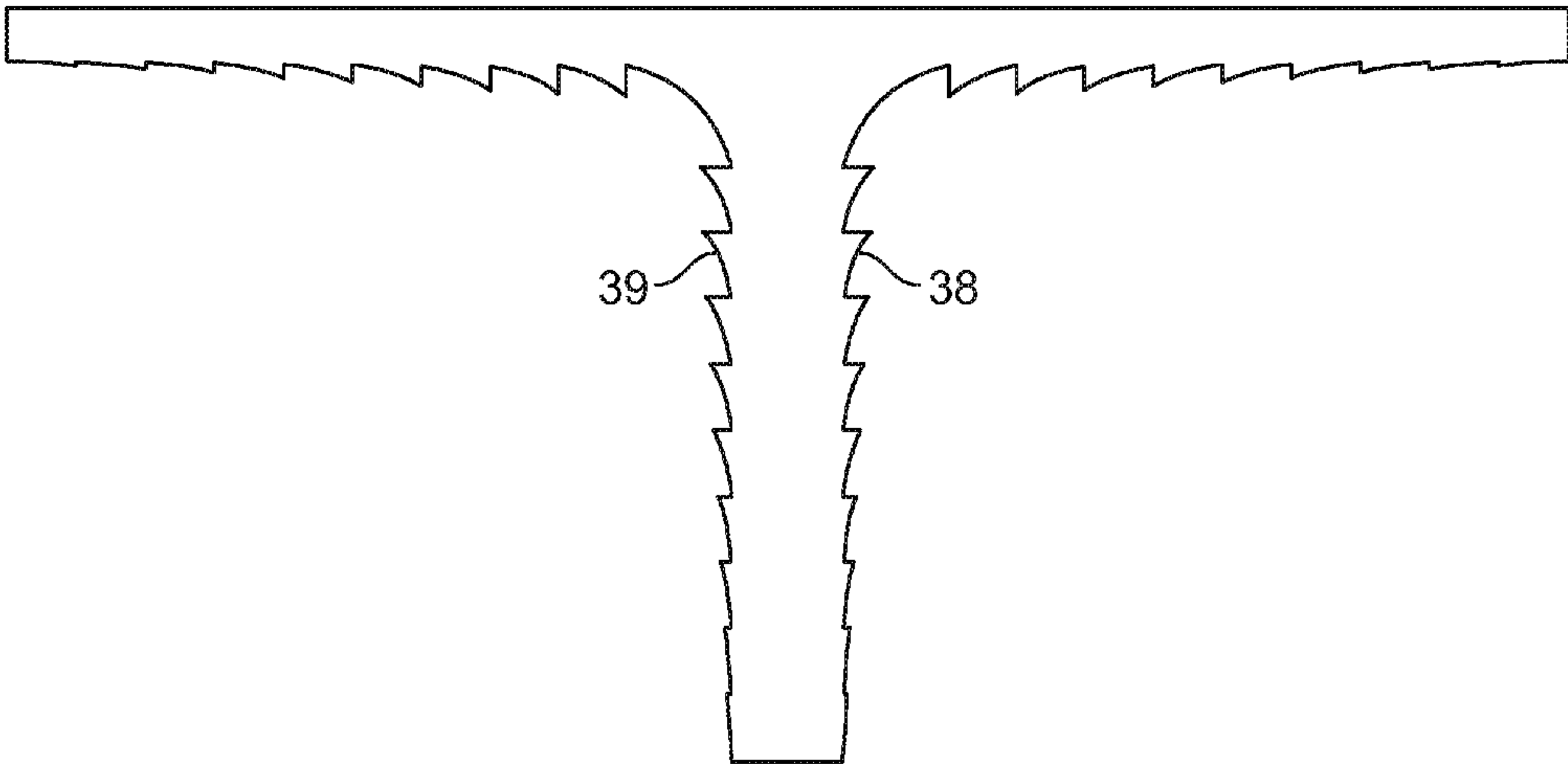
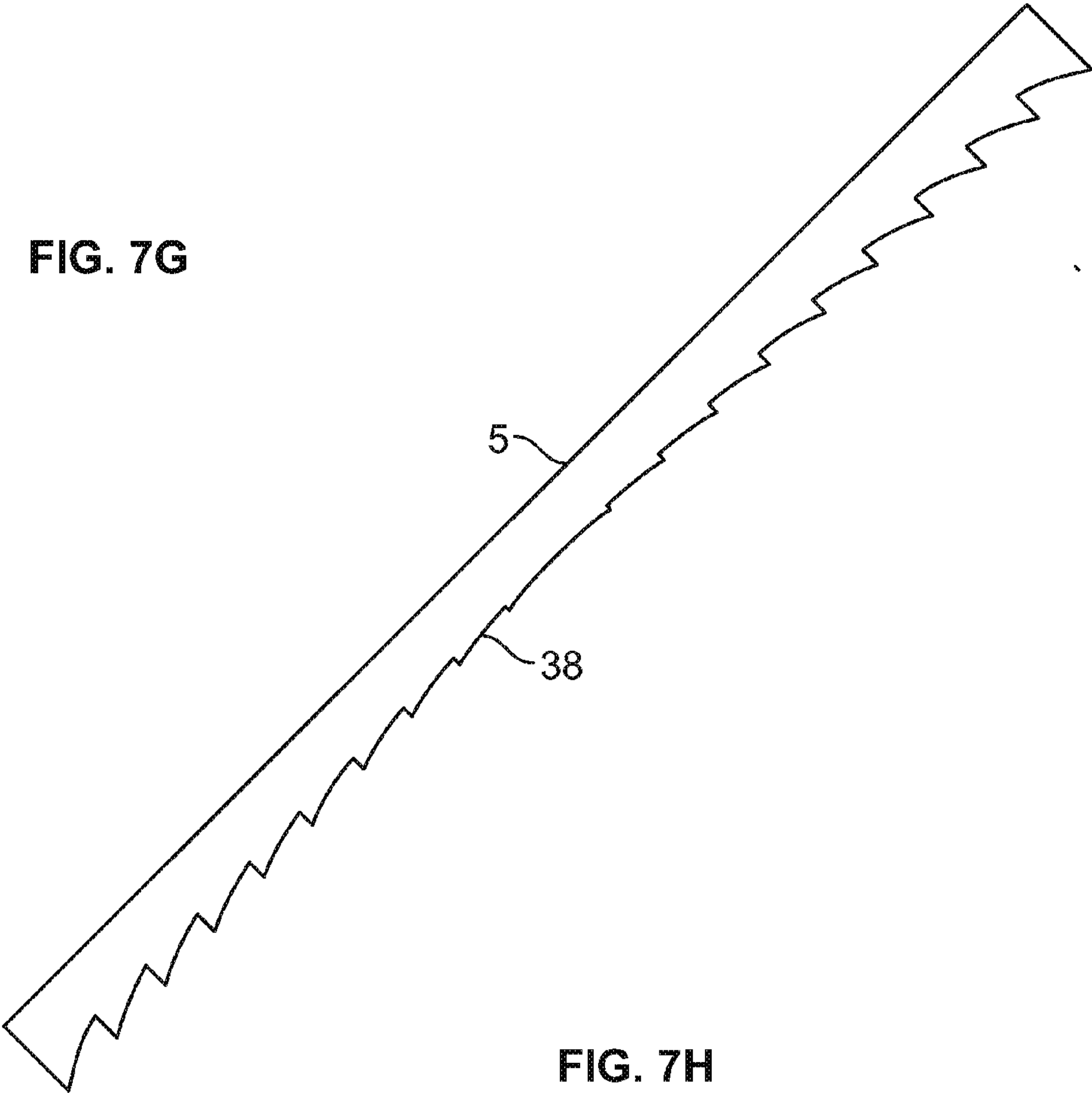
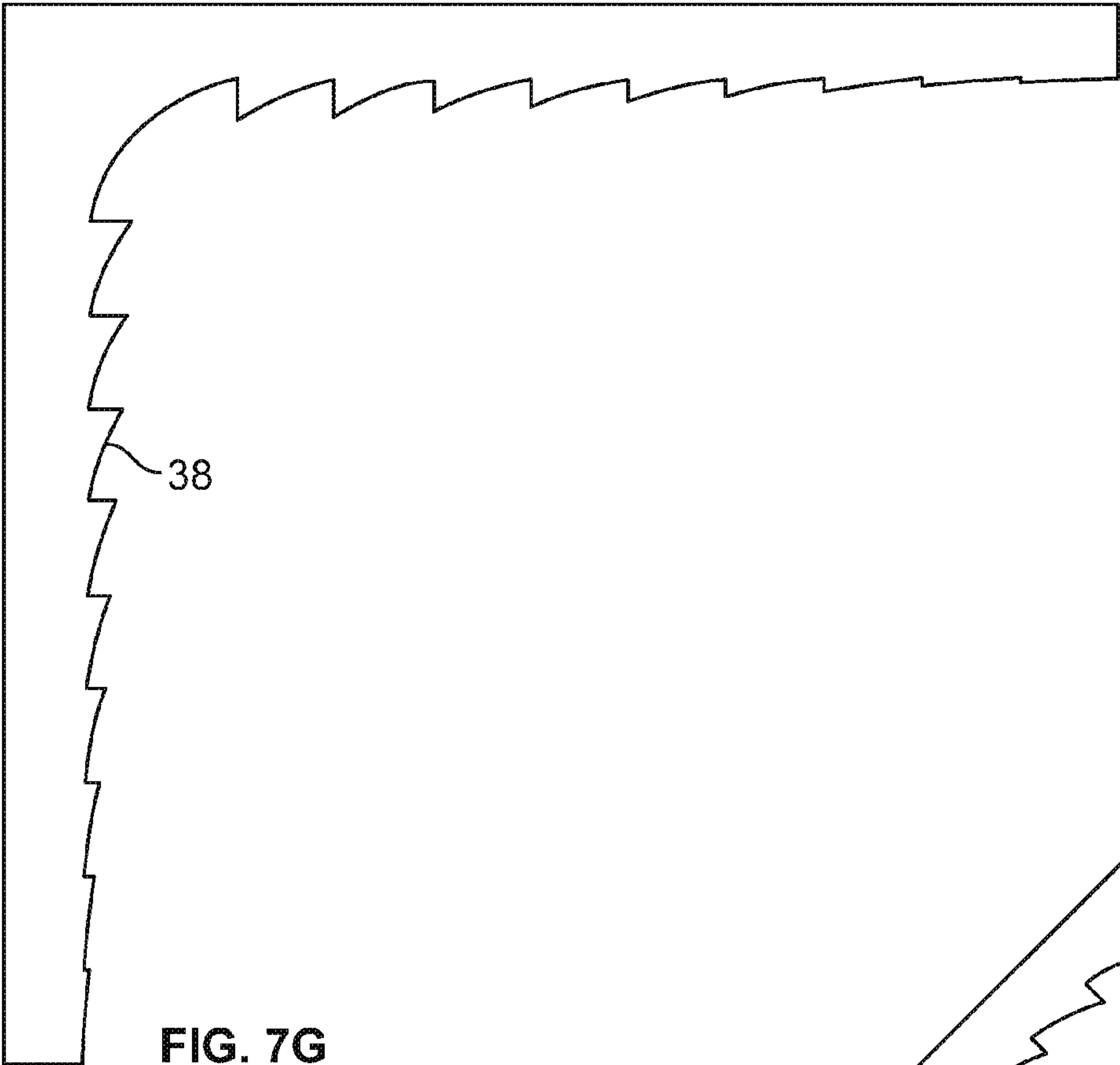


FIG. 7F



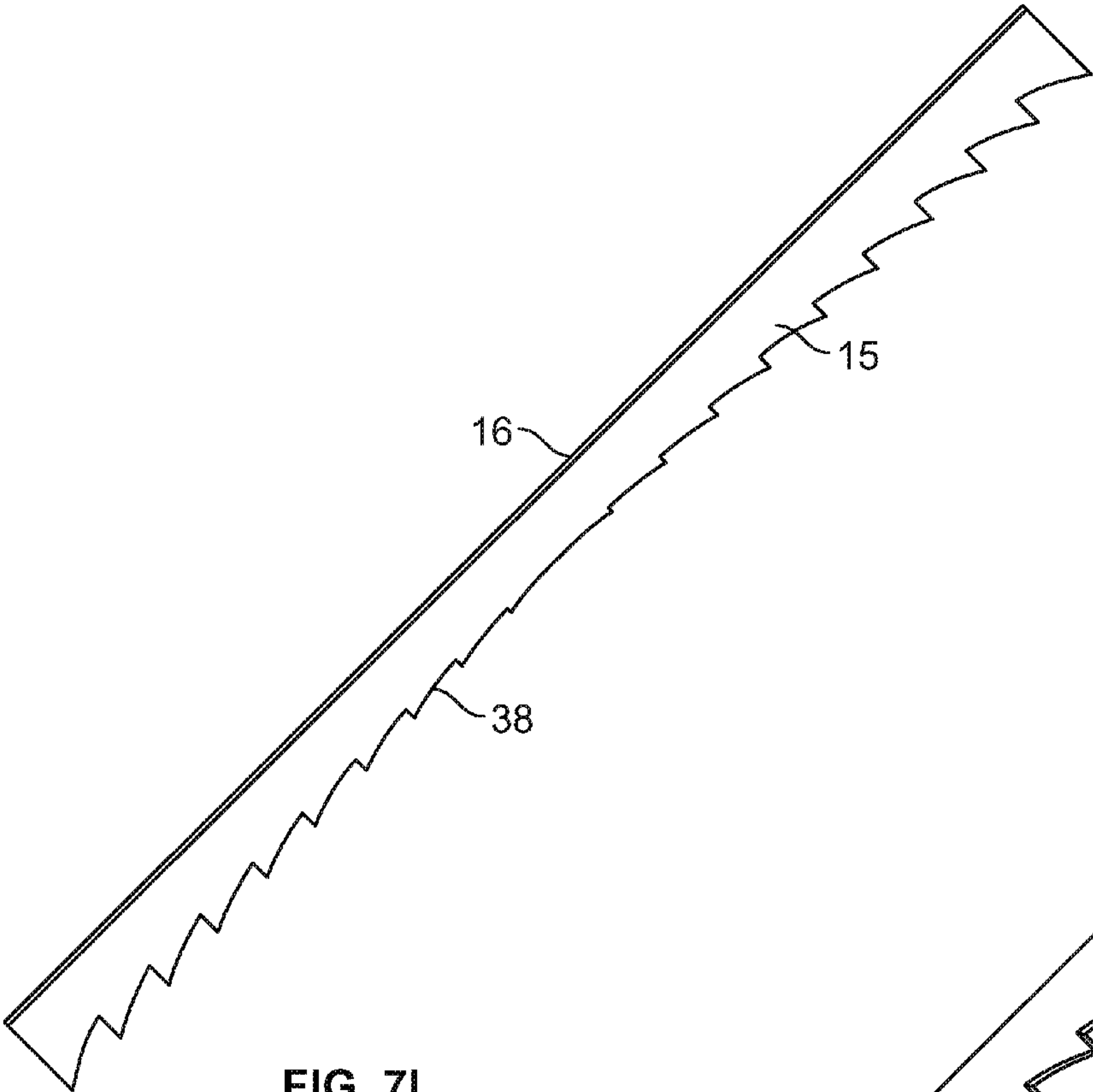


FIG. 7I

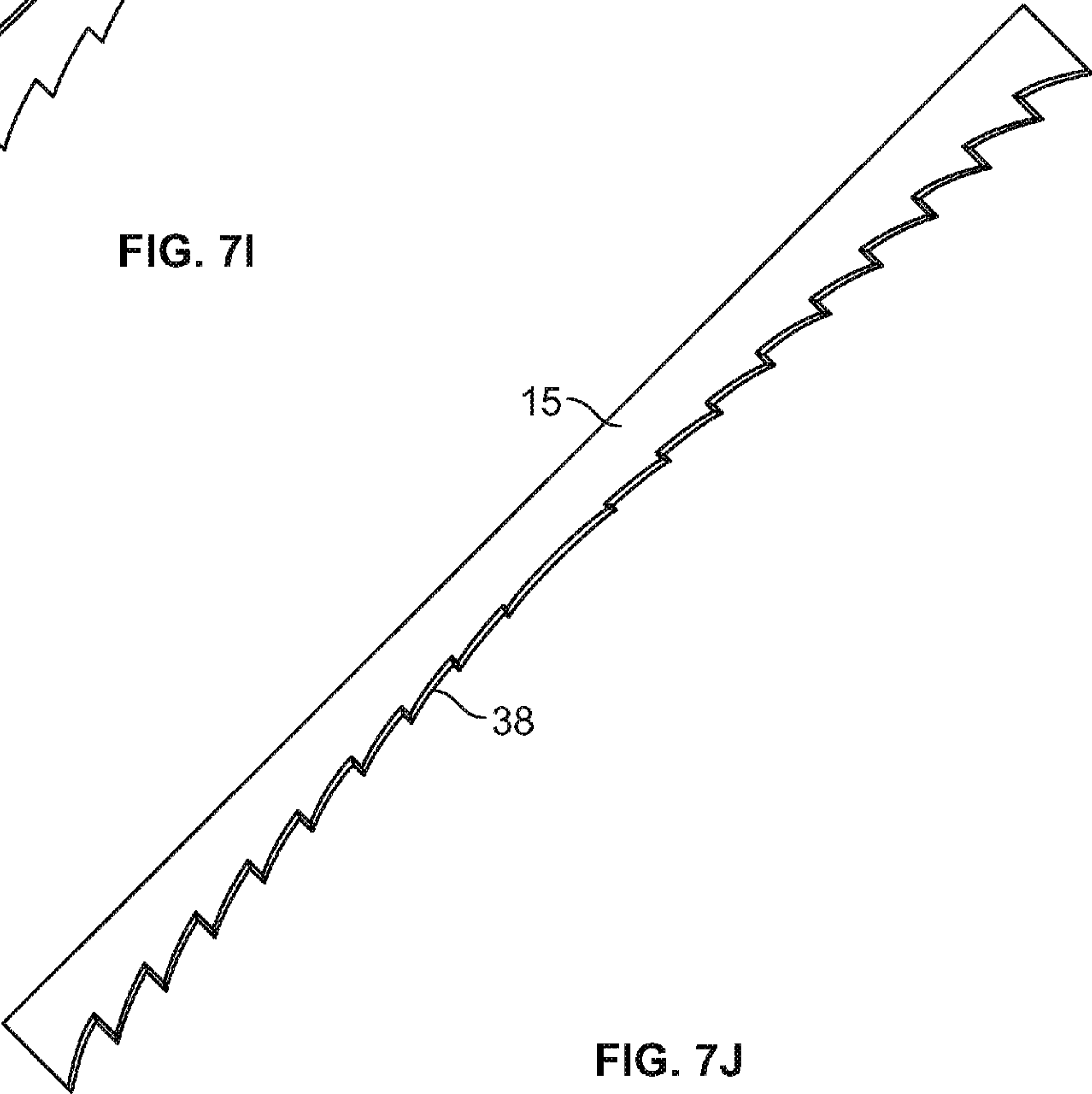


FIG. 7J

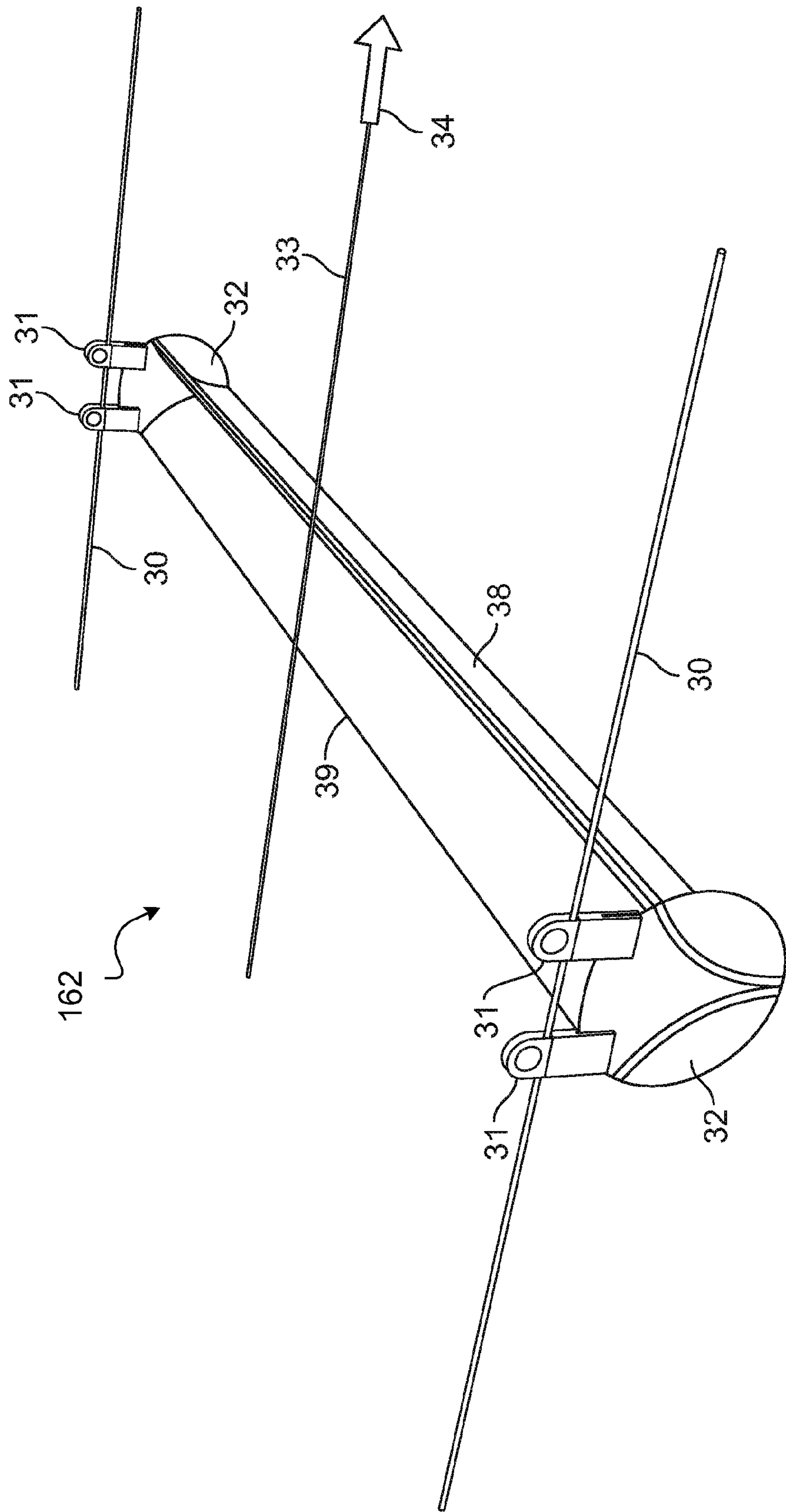
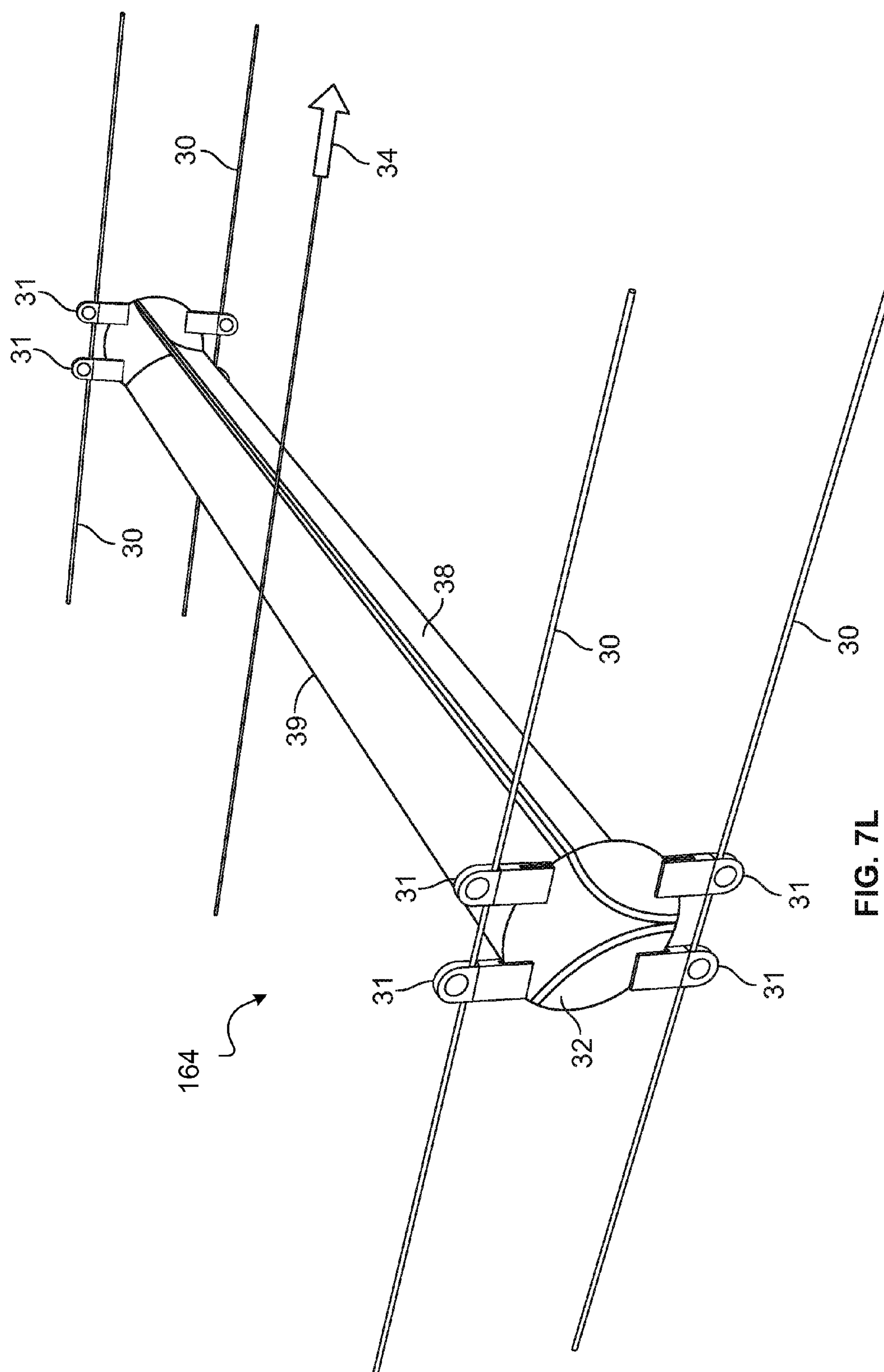


FIG. 7K



72
G.
F.

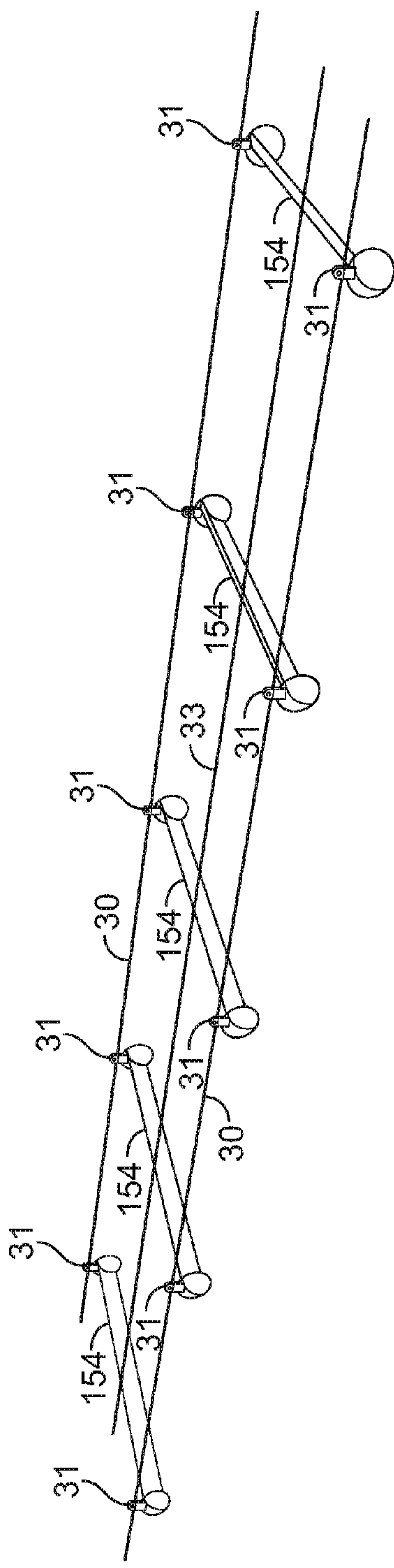


FIG. 8A

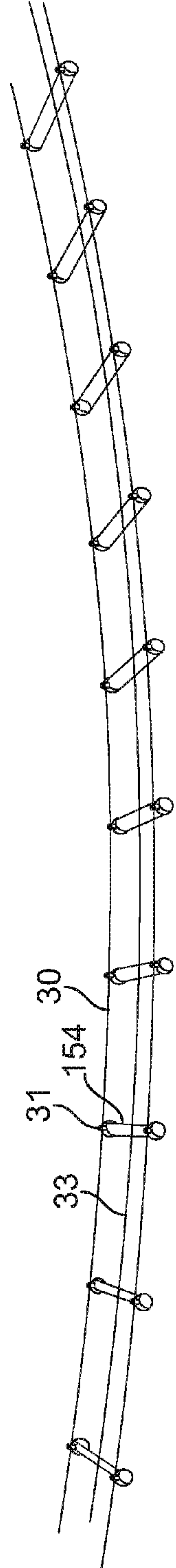


FIG. 8B

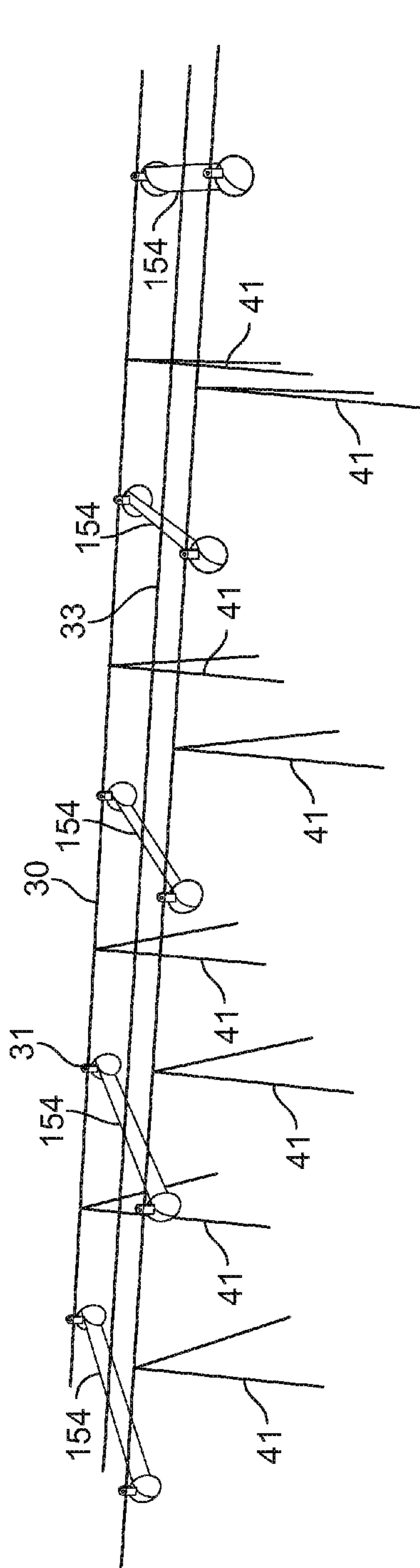


FIG. 8C

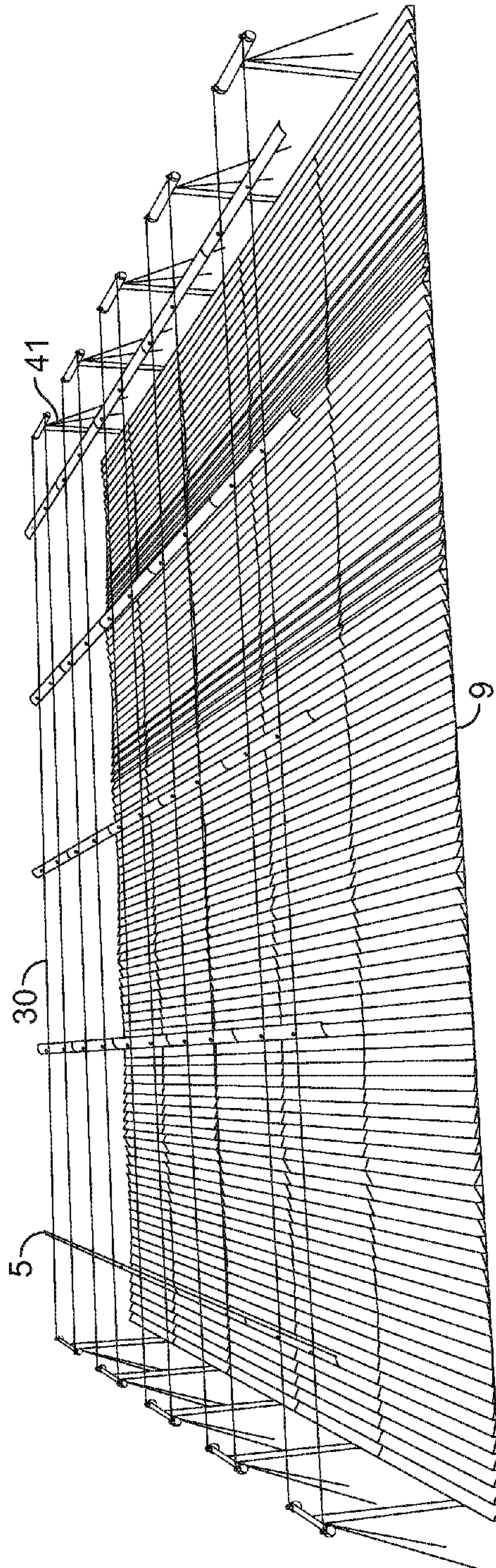


FIG. 9

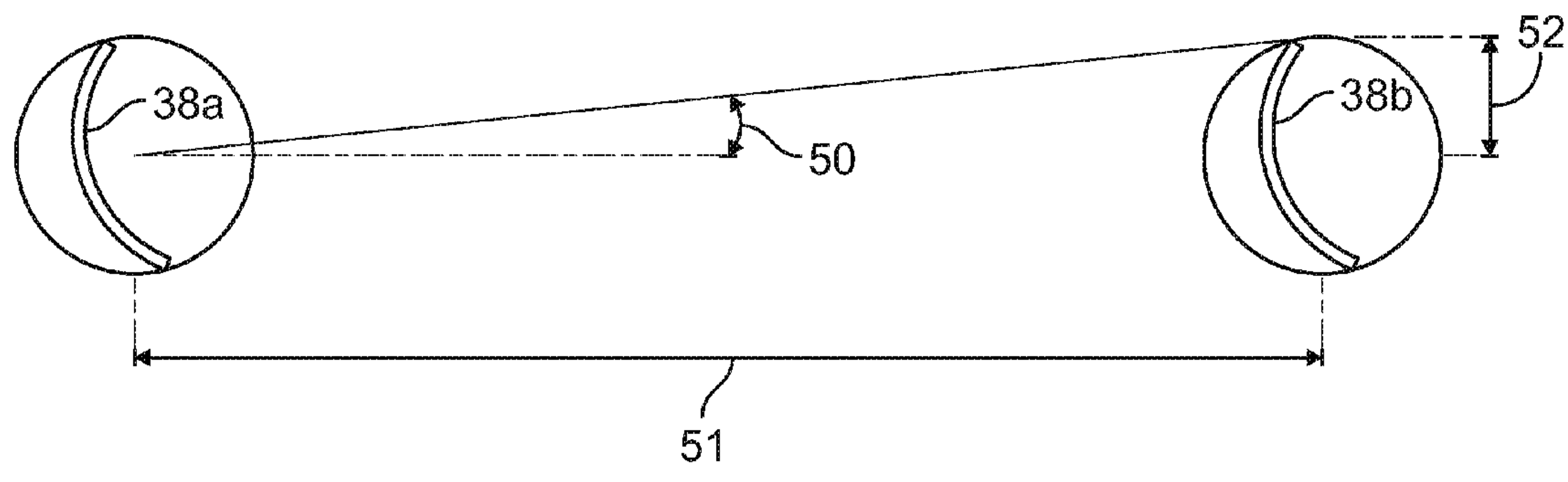


FIG. 10

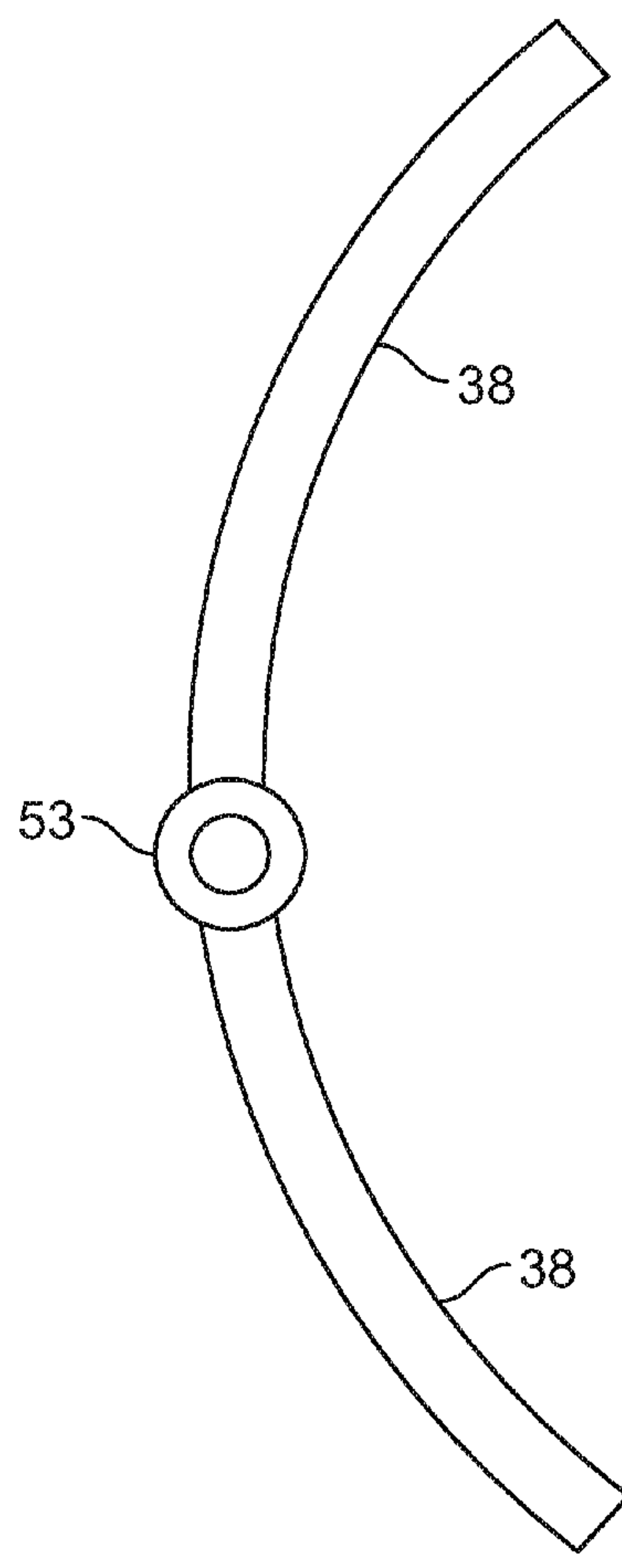


FIG. 11A

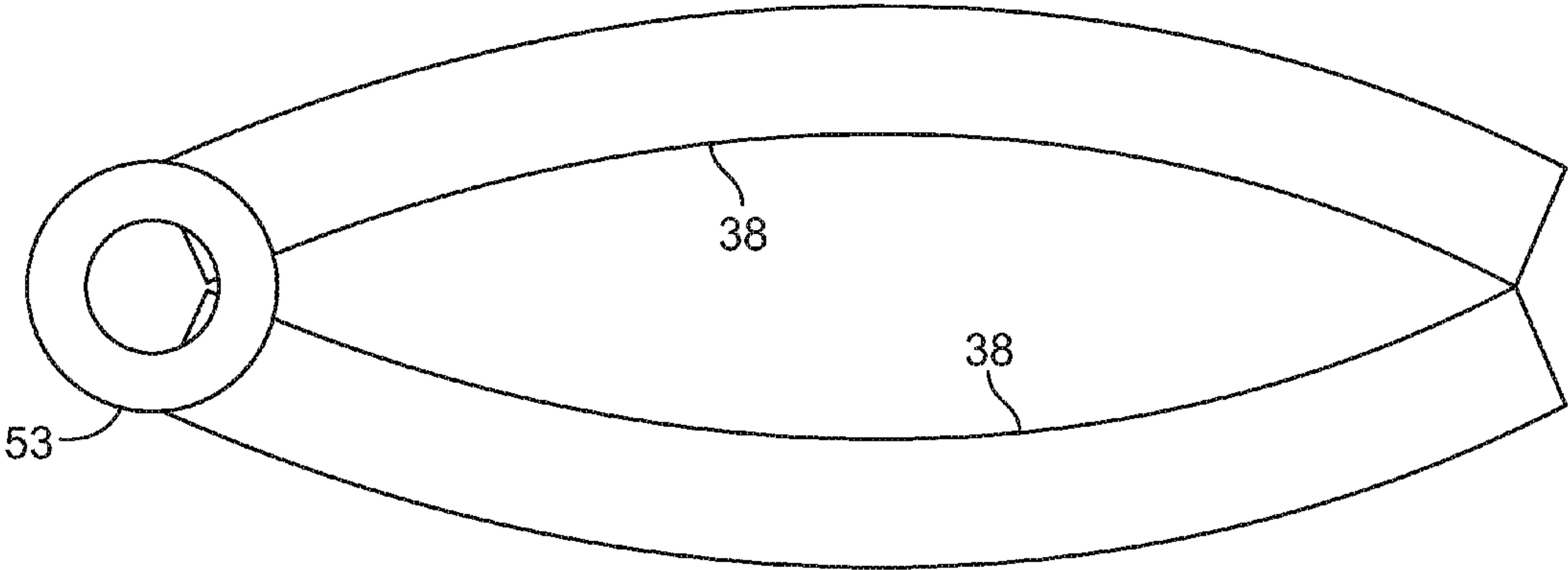


FIG. 11B

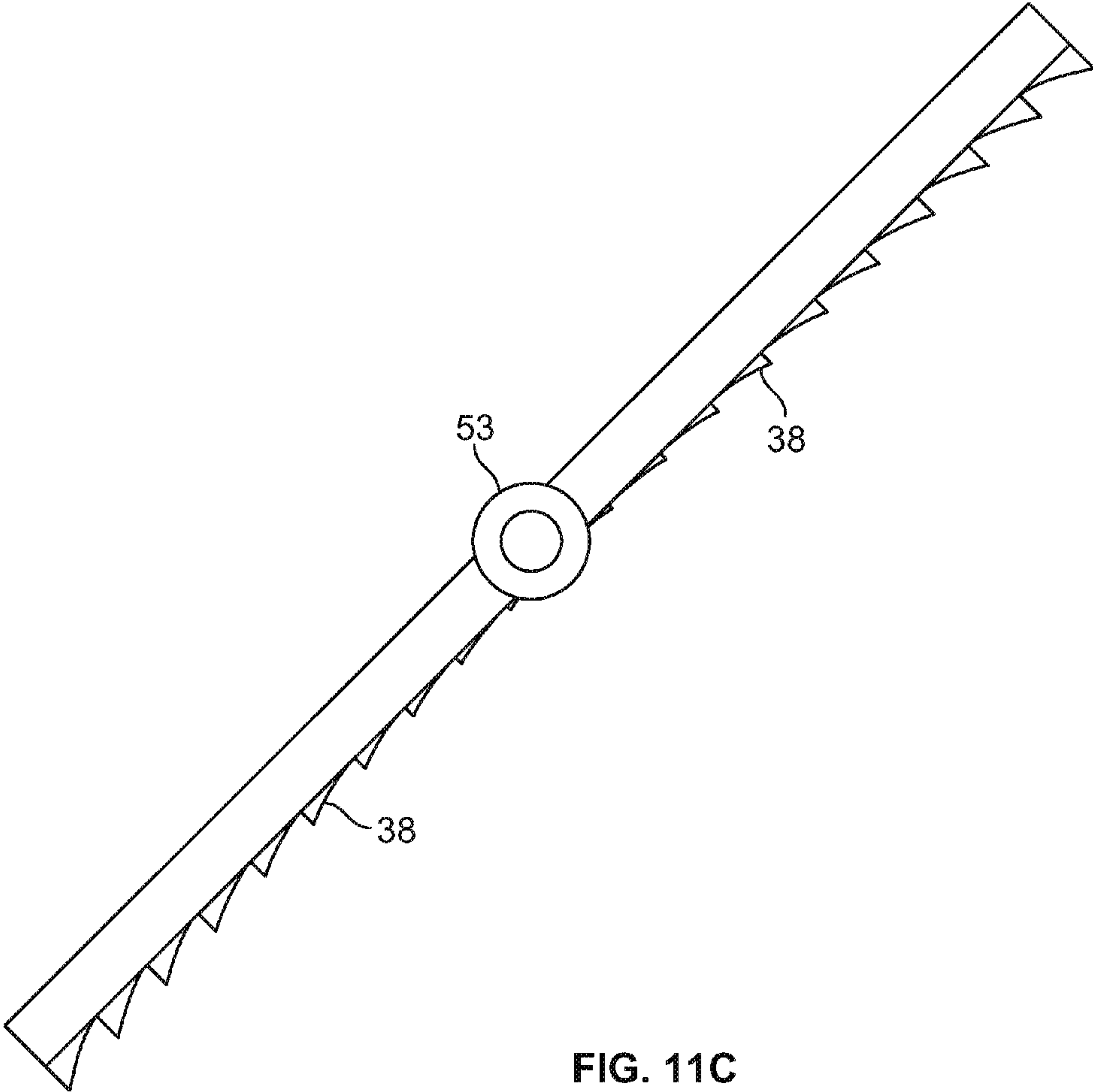


FIG. 11C

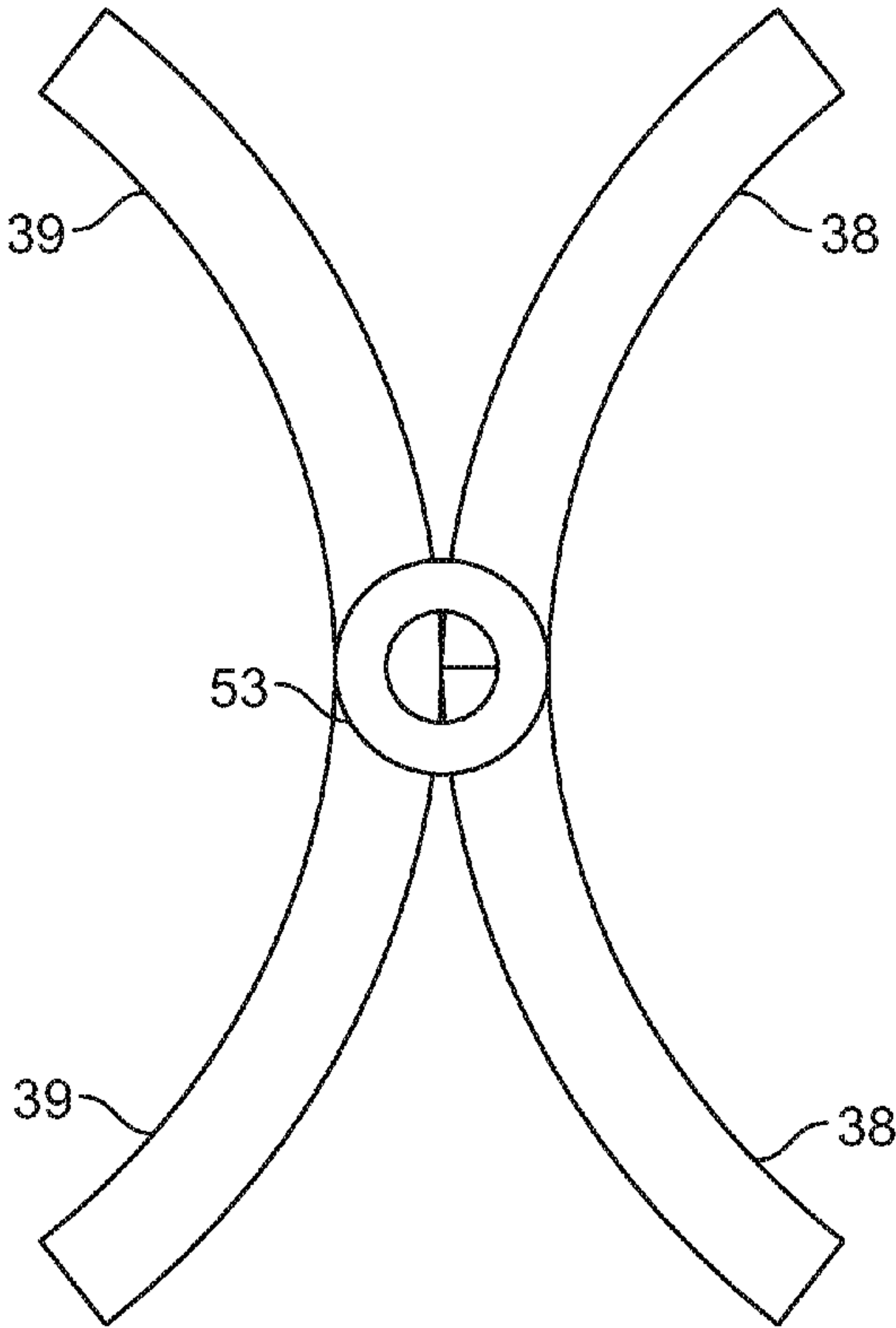
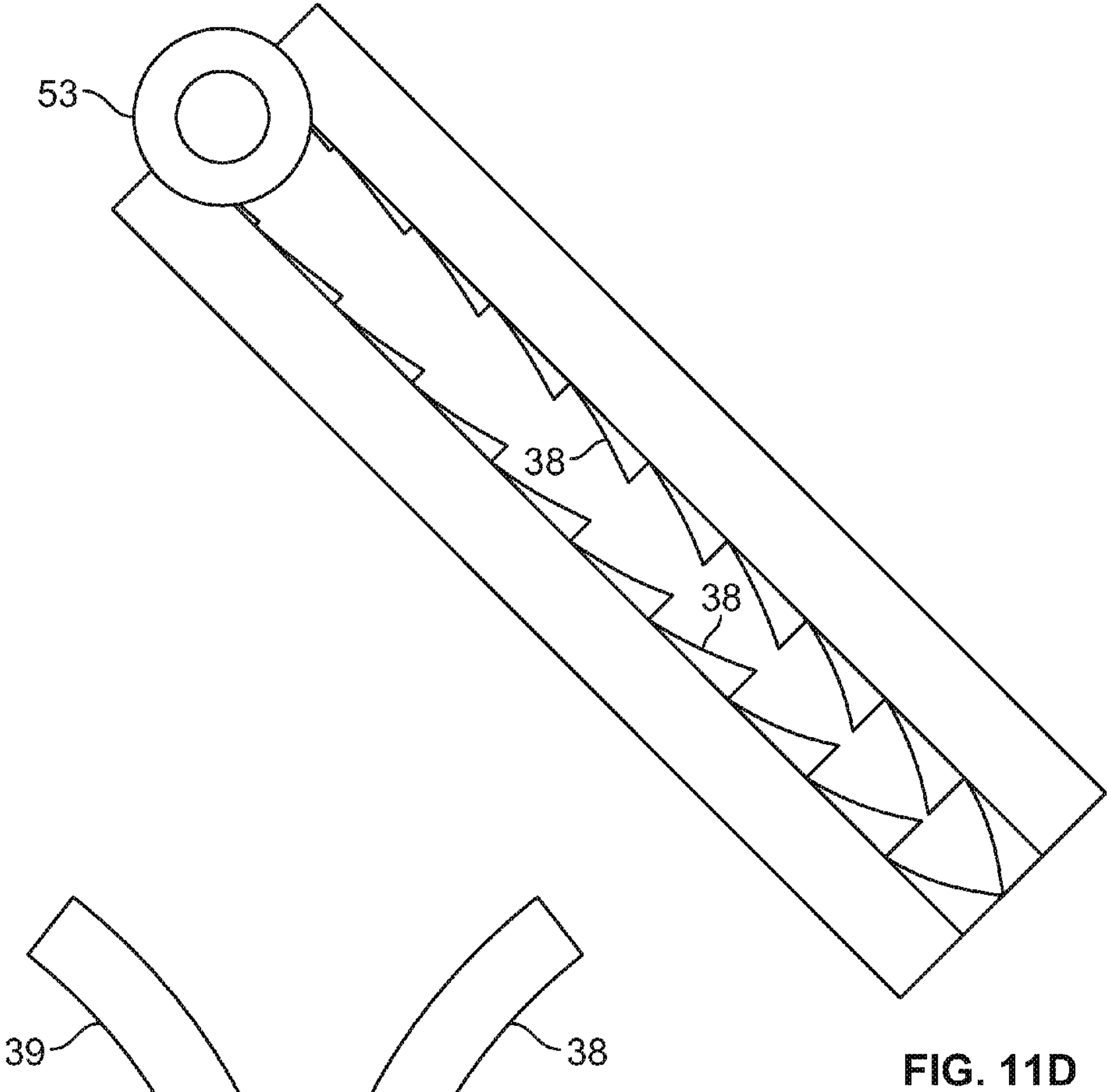


FIG. 12A

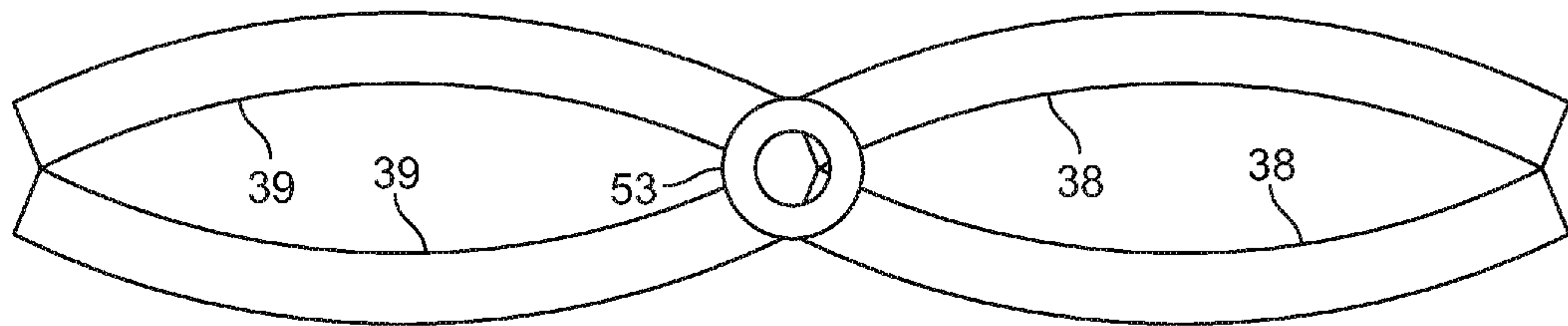


FIG. 12B

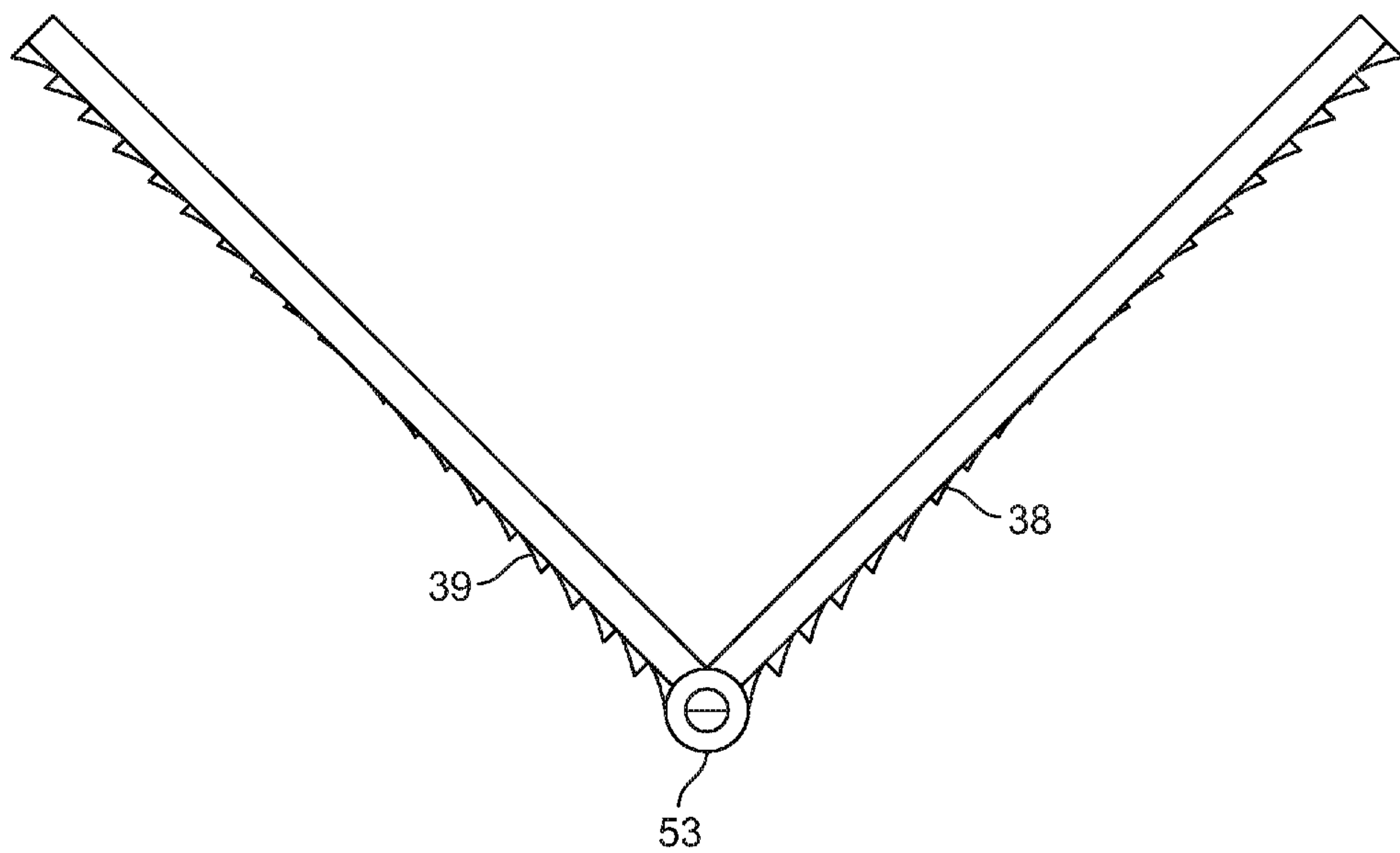


FIG. 12C

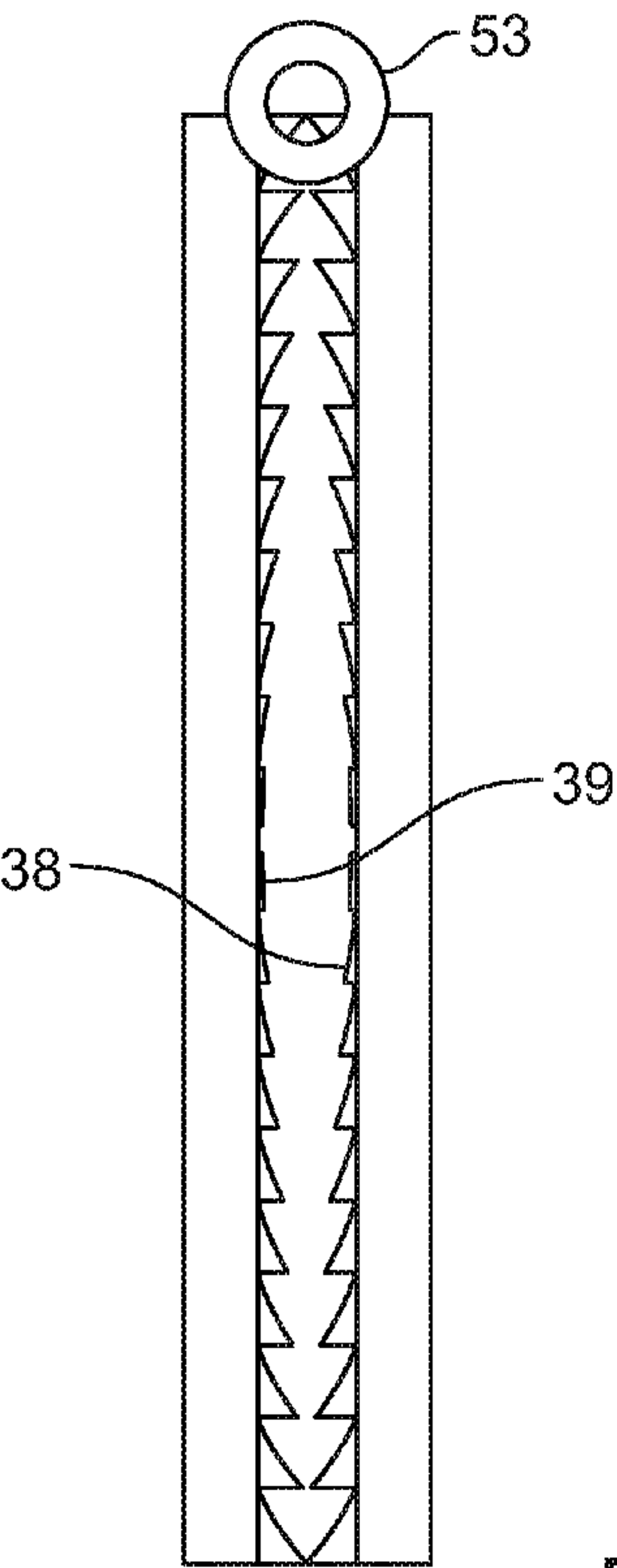


FIG. 12D

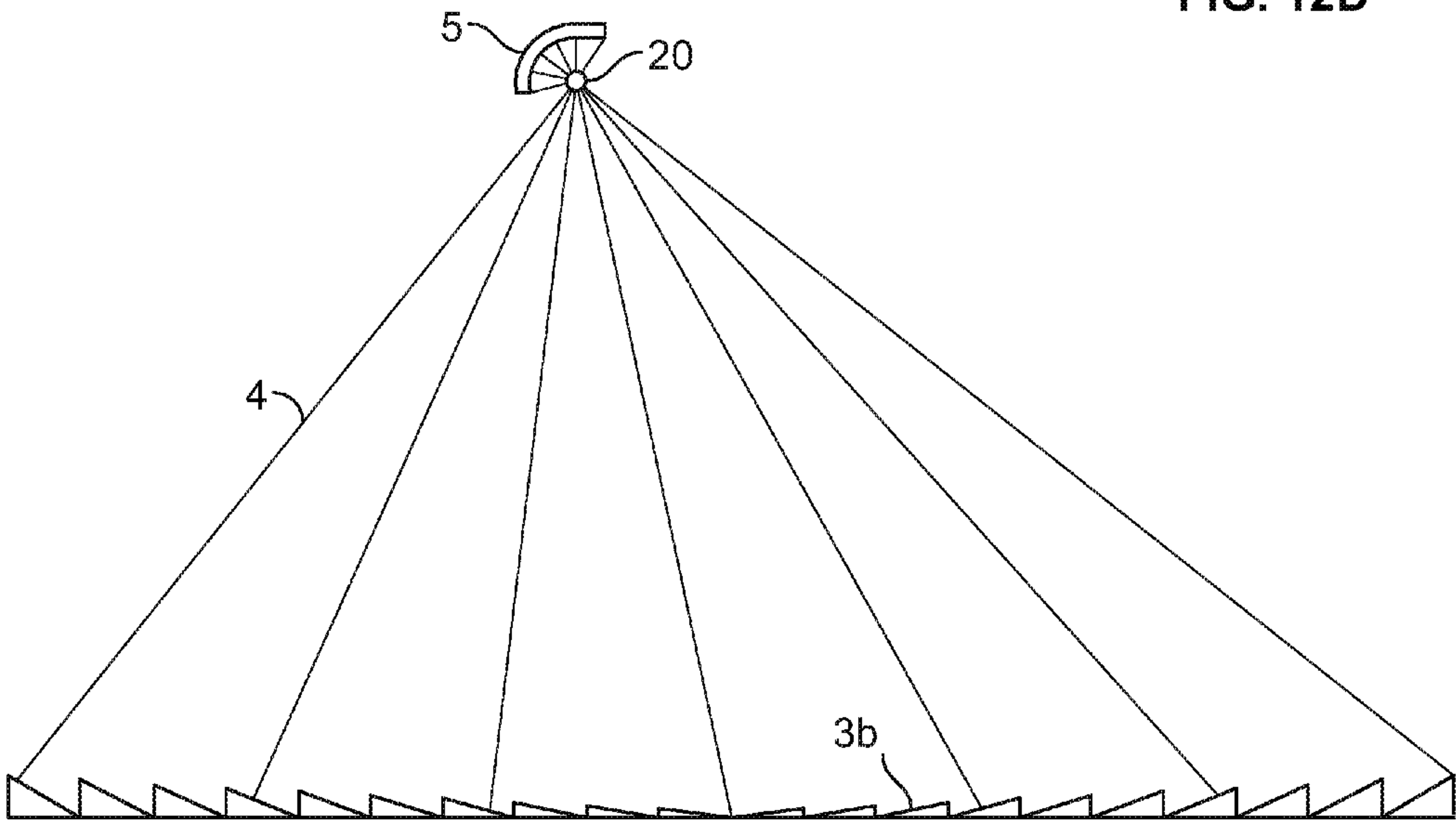


FIG. 13A

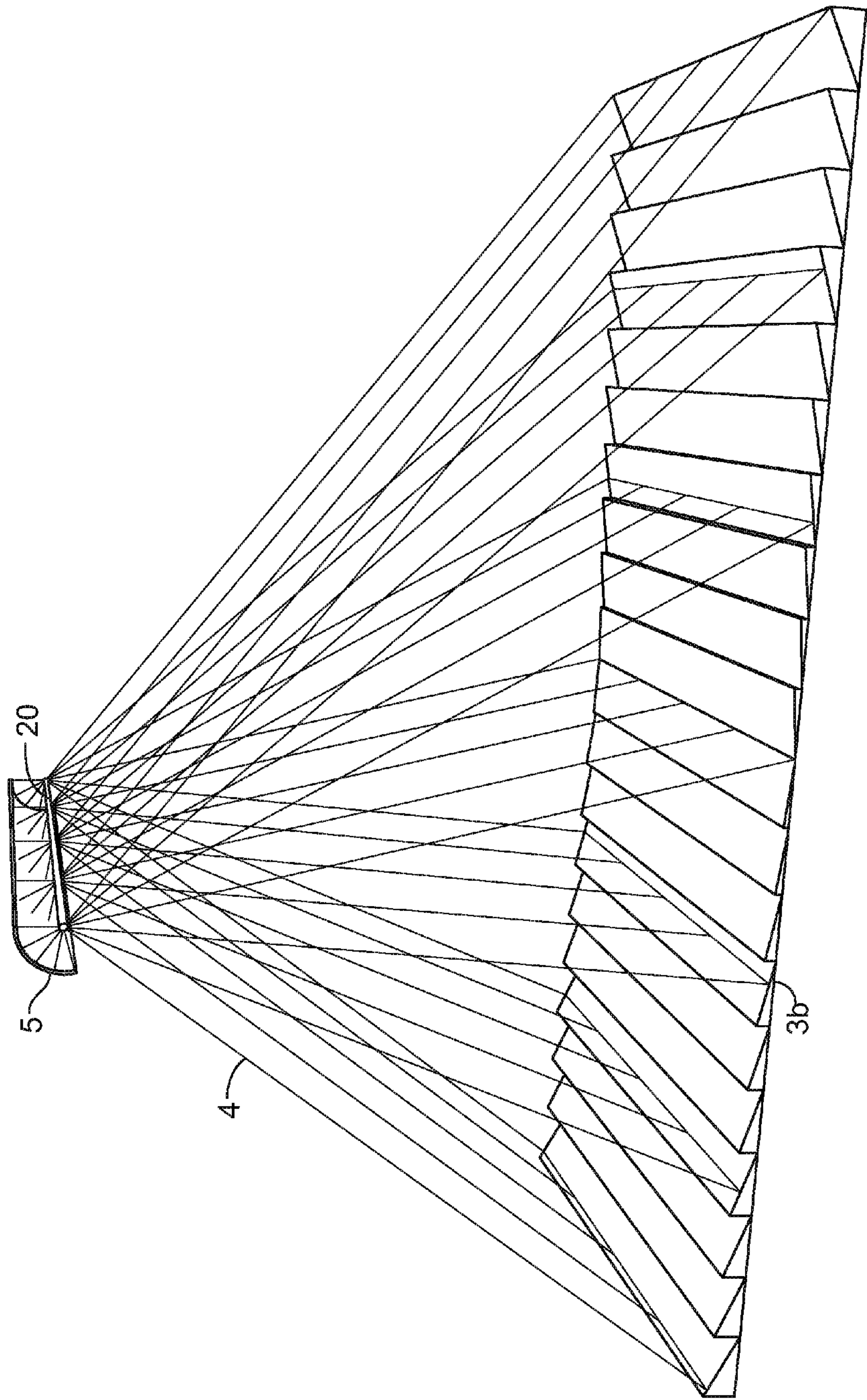


FIG. 13B

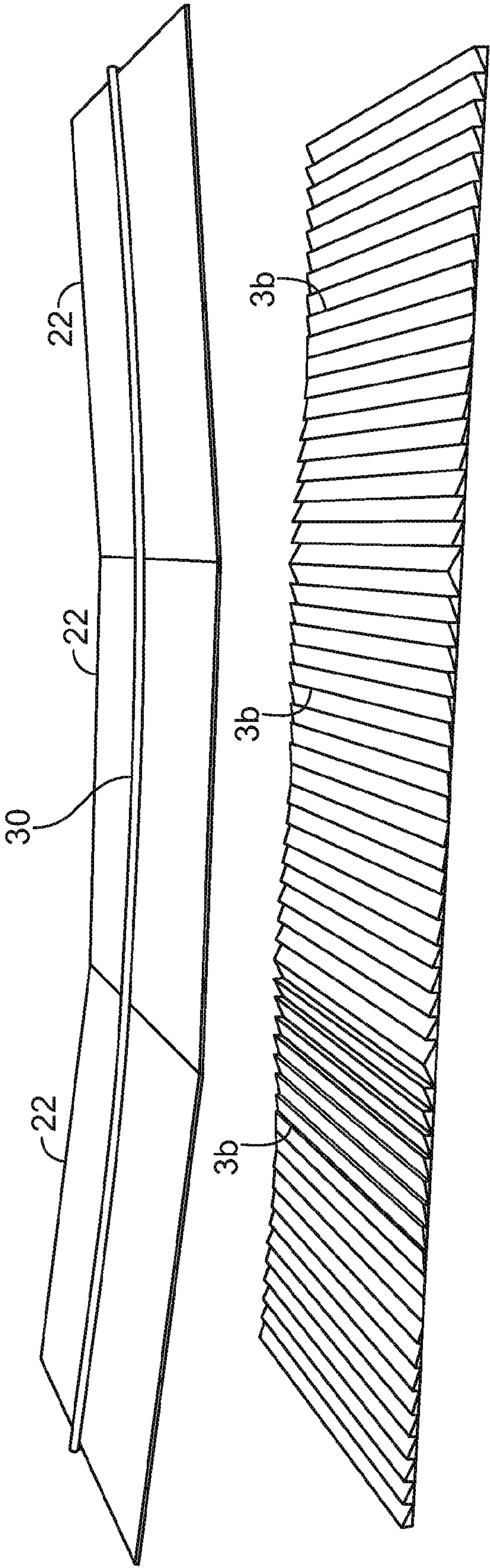


FIG. 13C

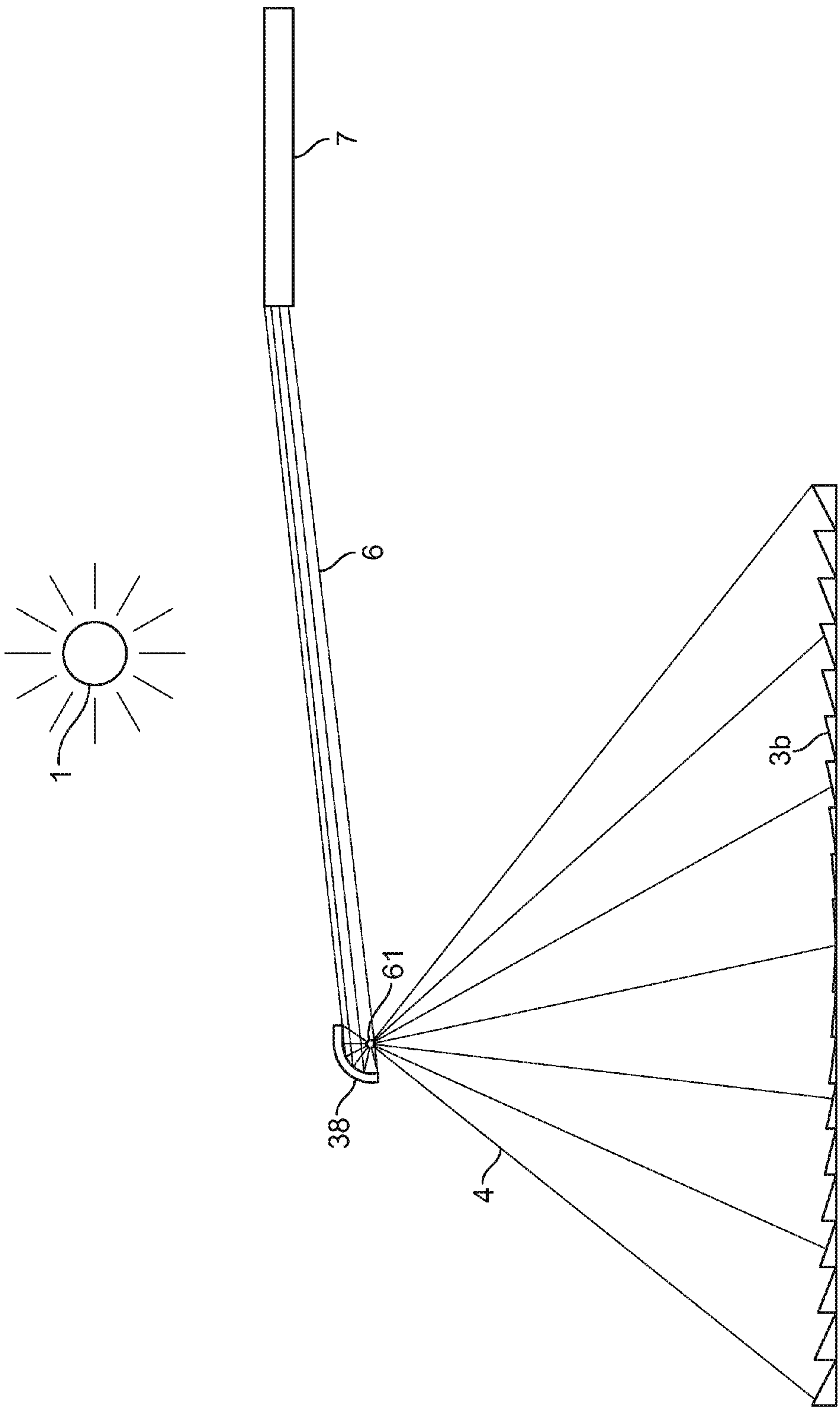
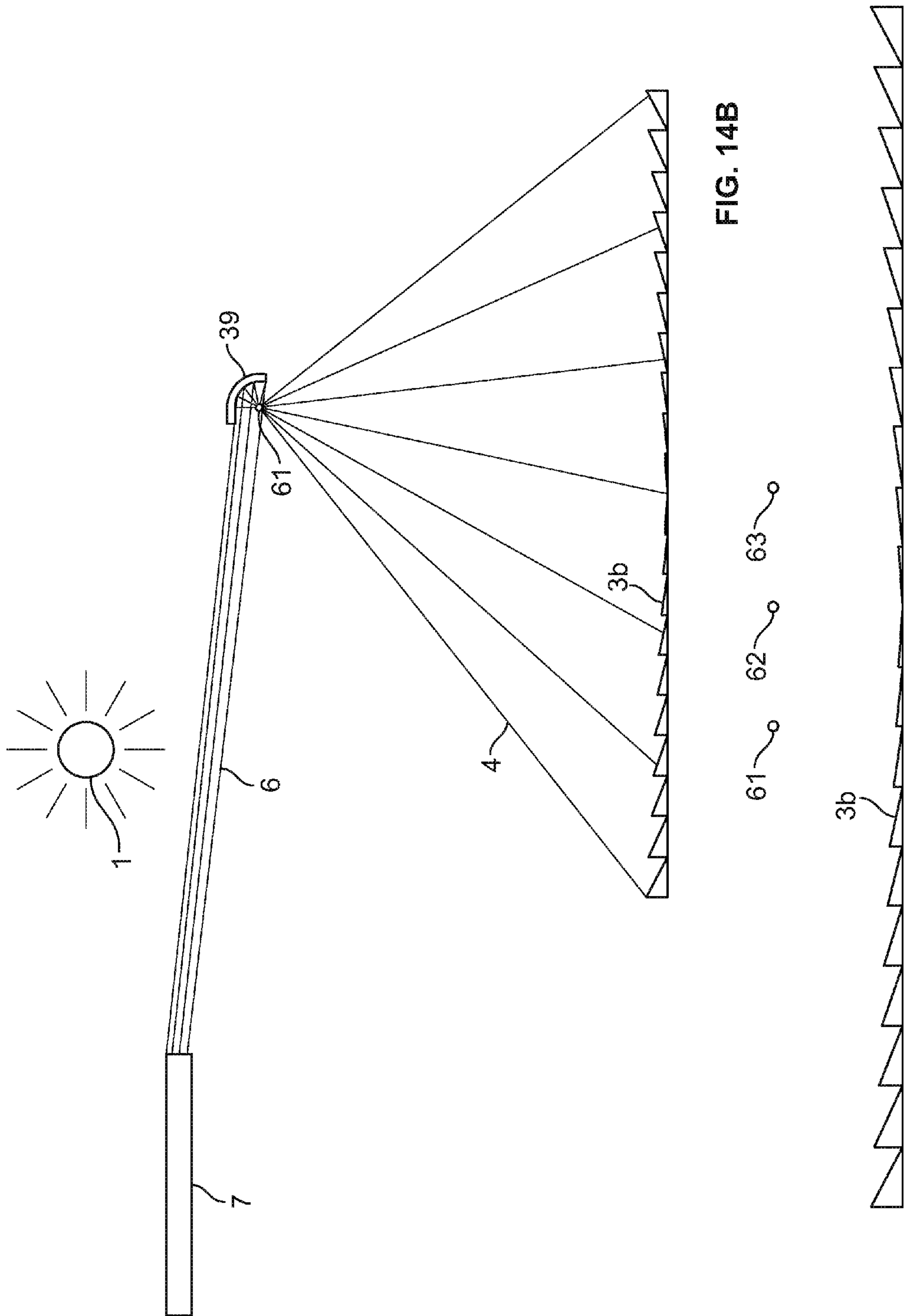


FIG. 14A



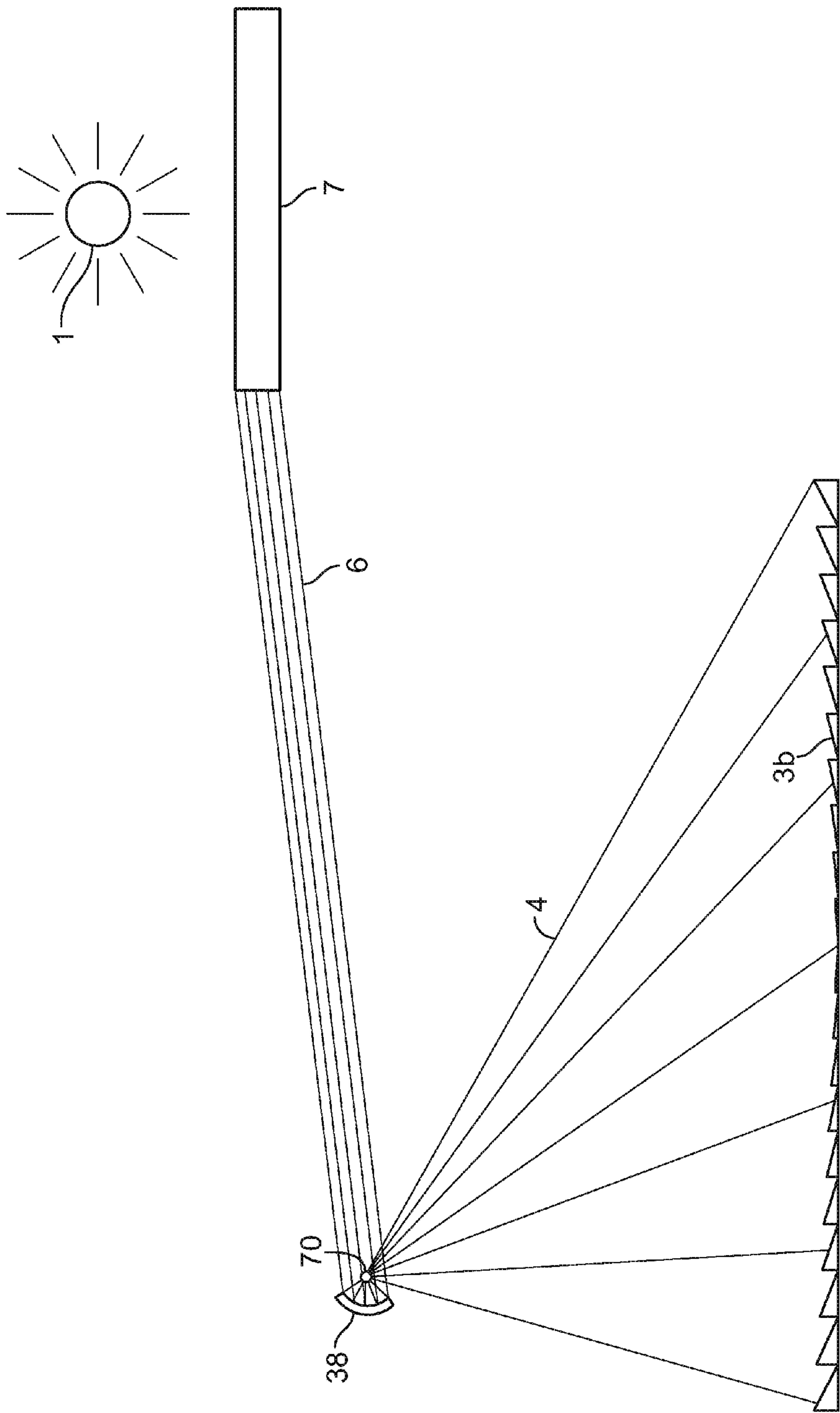


FIG. 15A

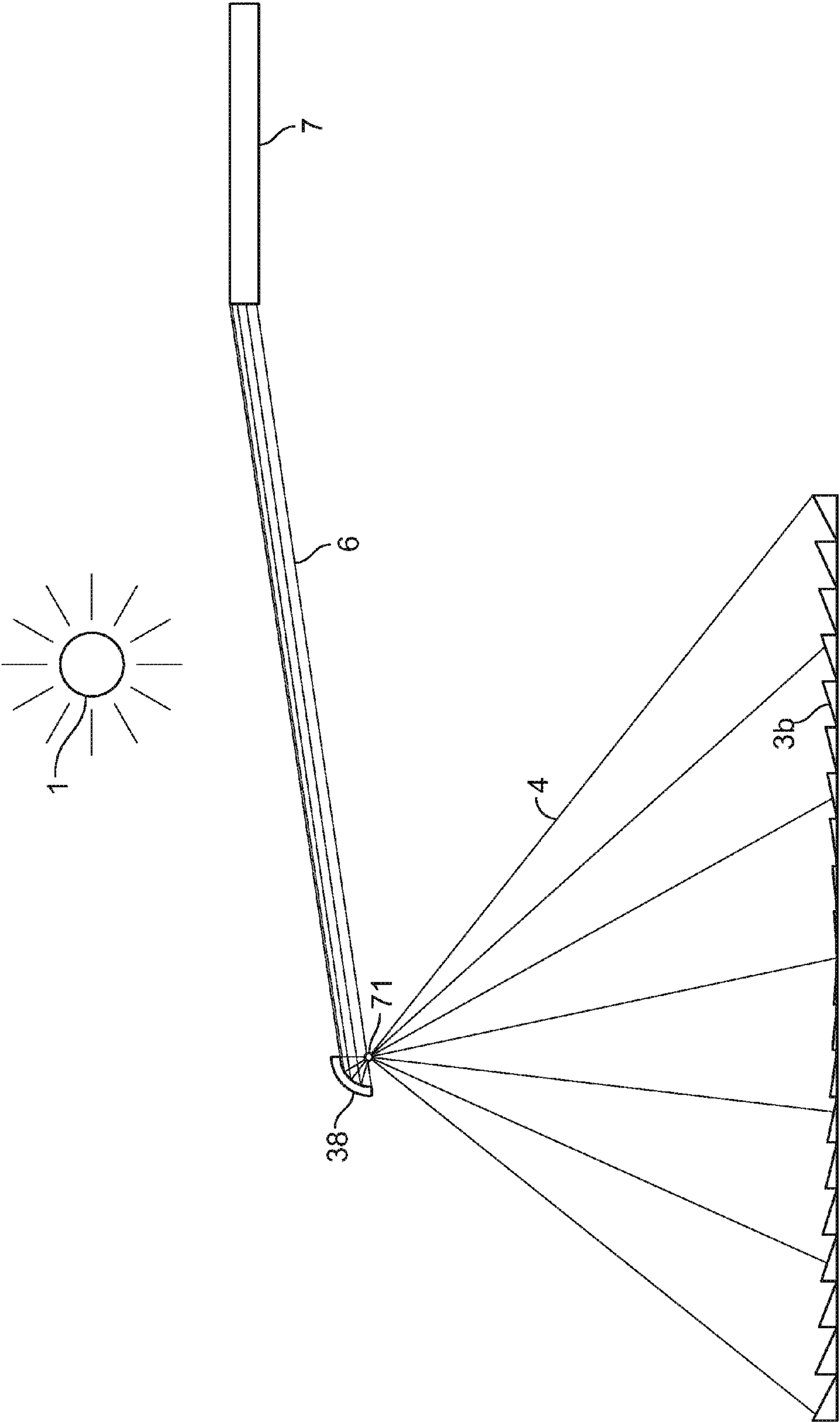


FIG. 15B

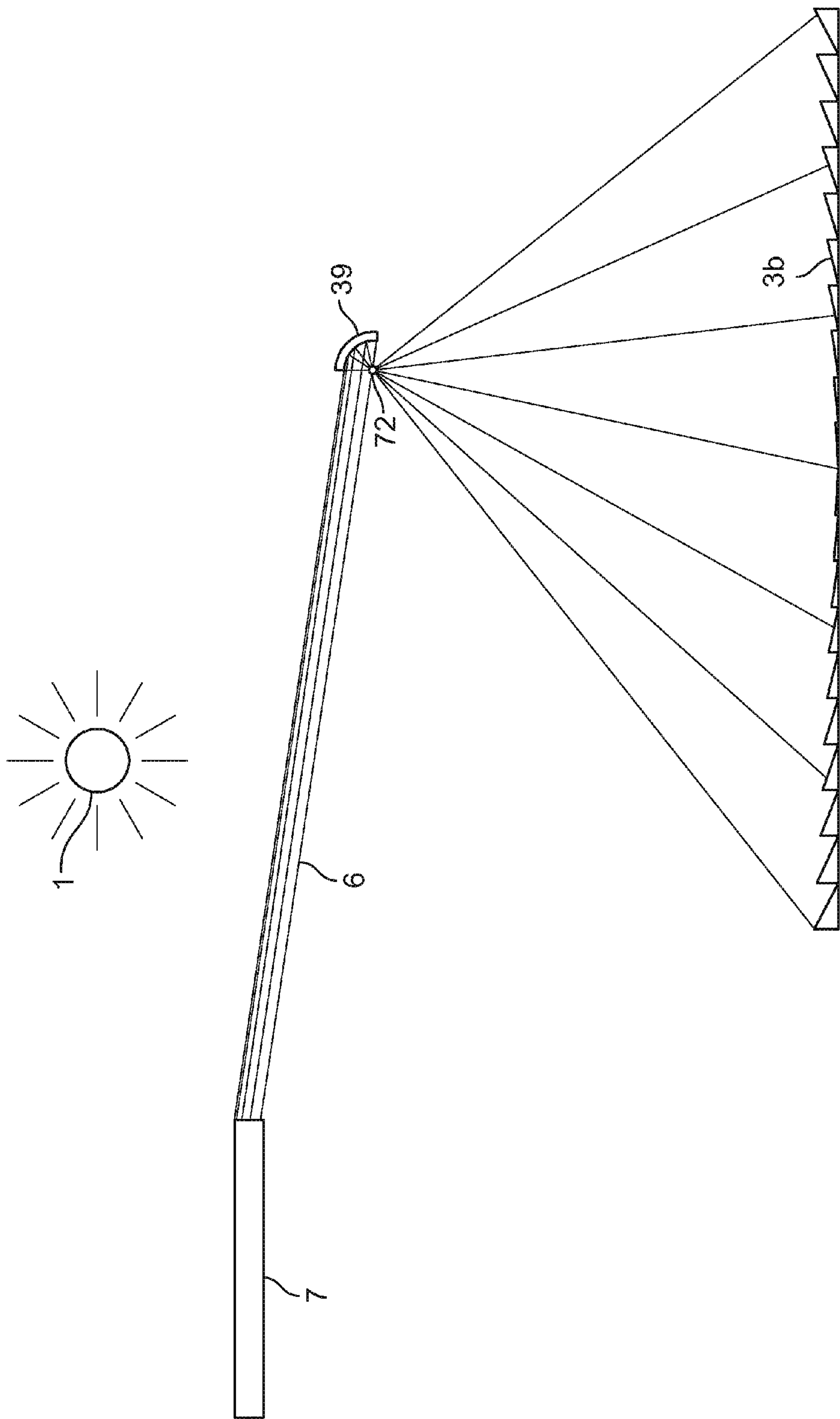


FIG. 15C

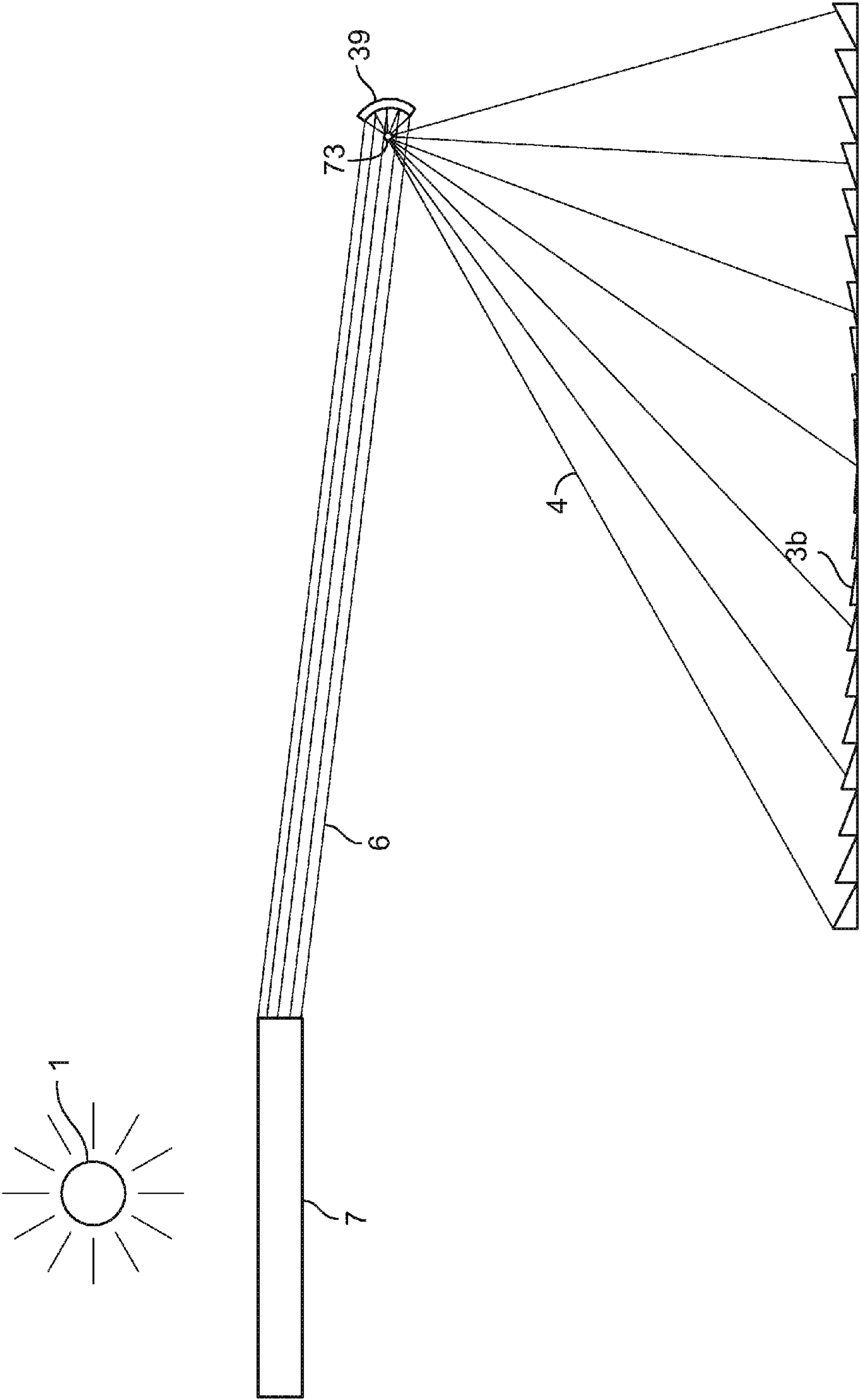


FIG. 15D

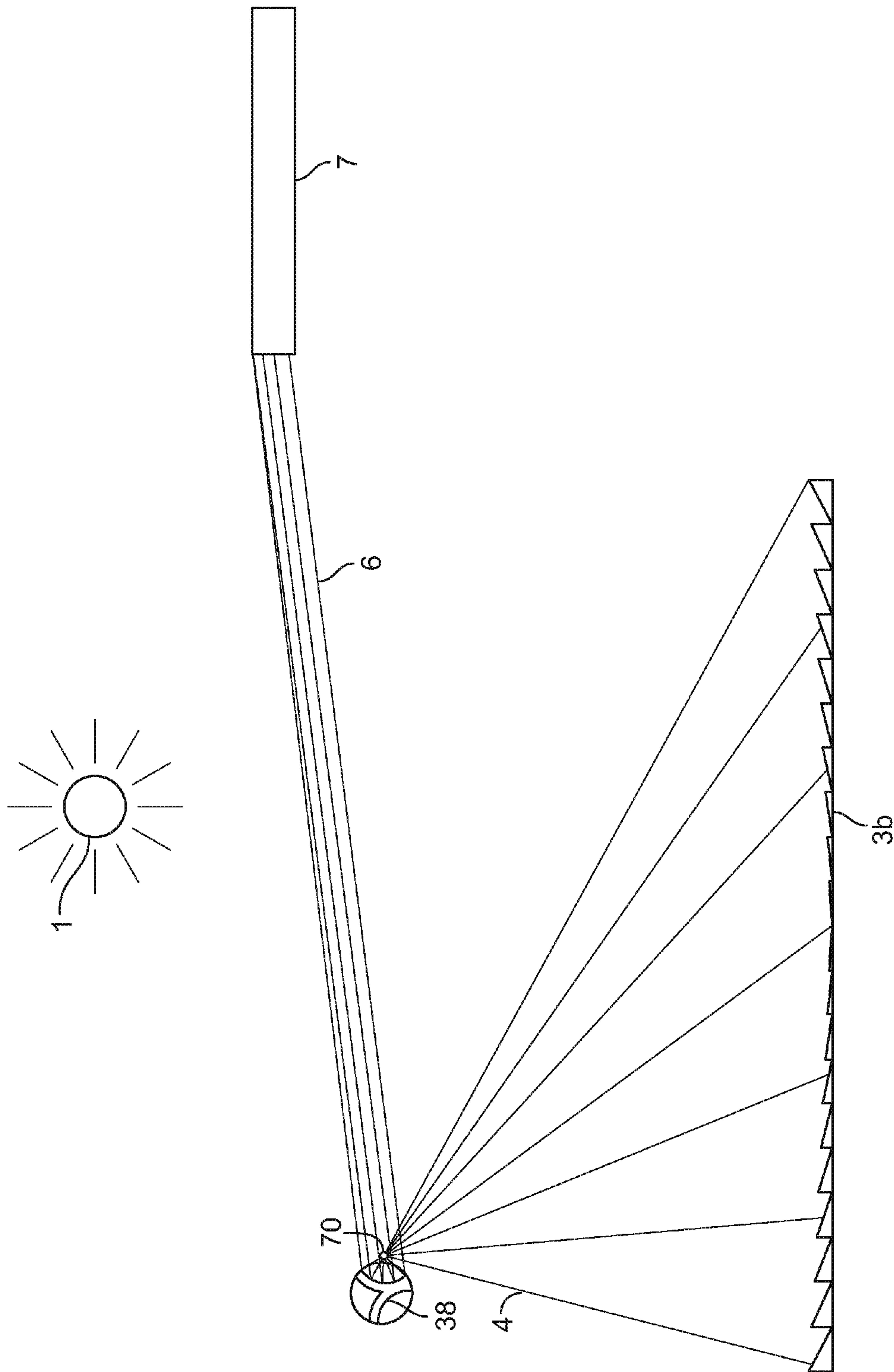


FIG. 16A

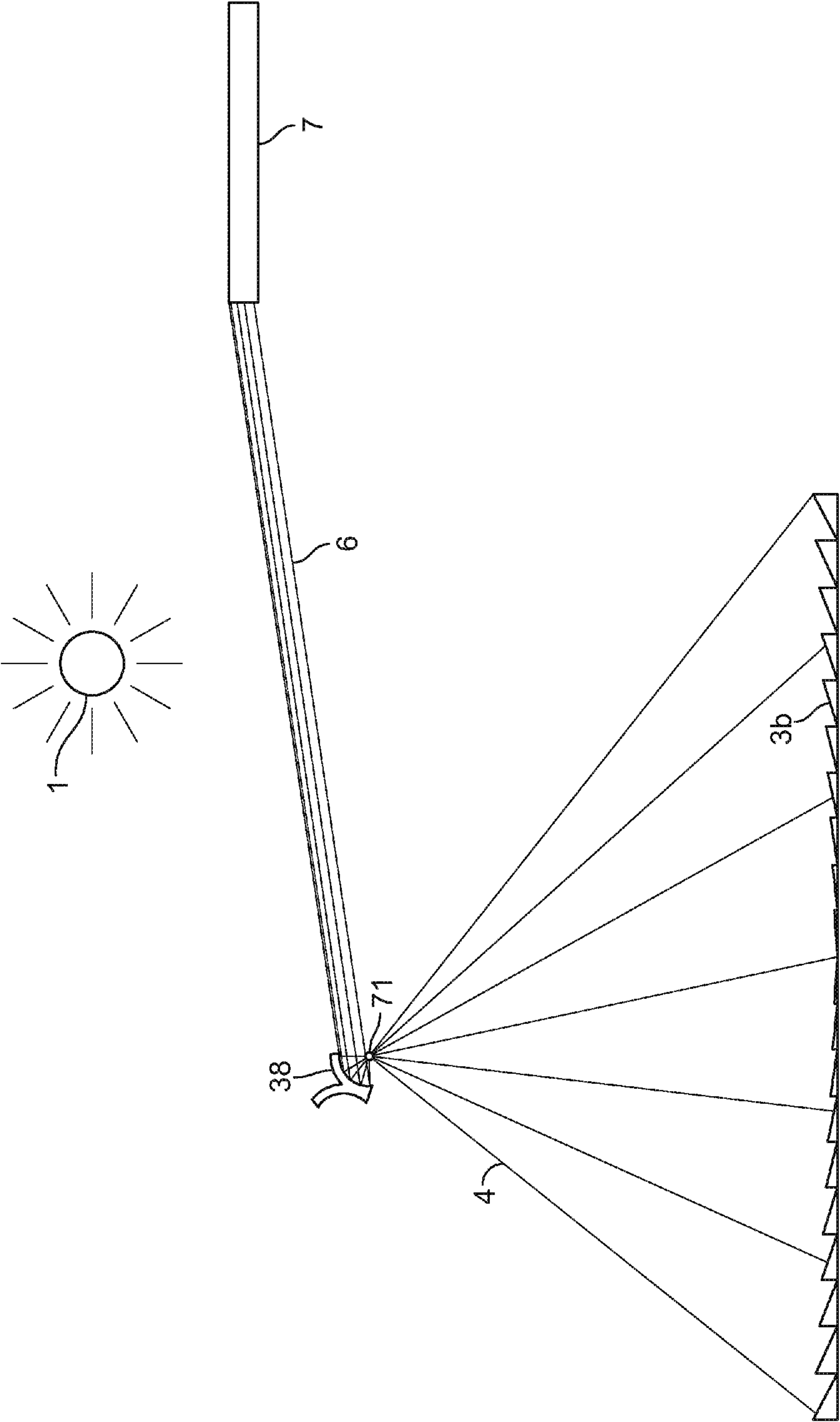


FIG. 16B

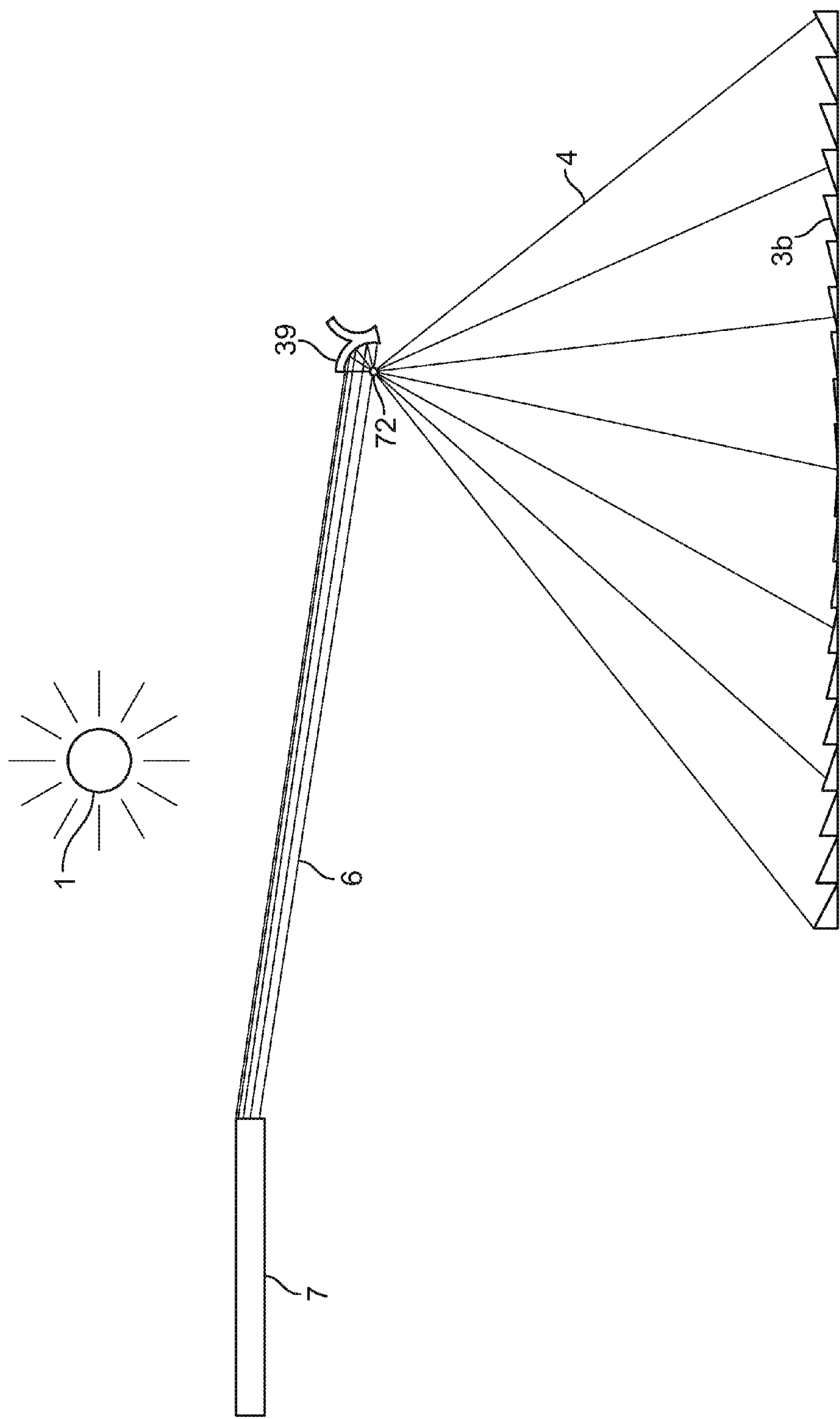


FIG. 16C

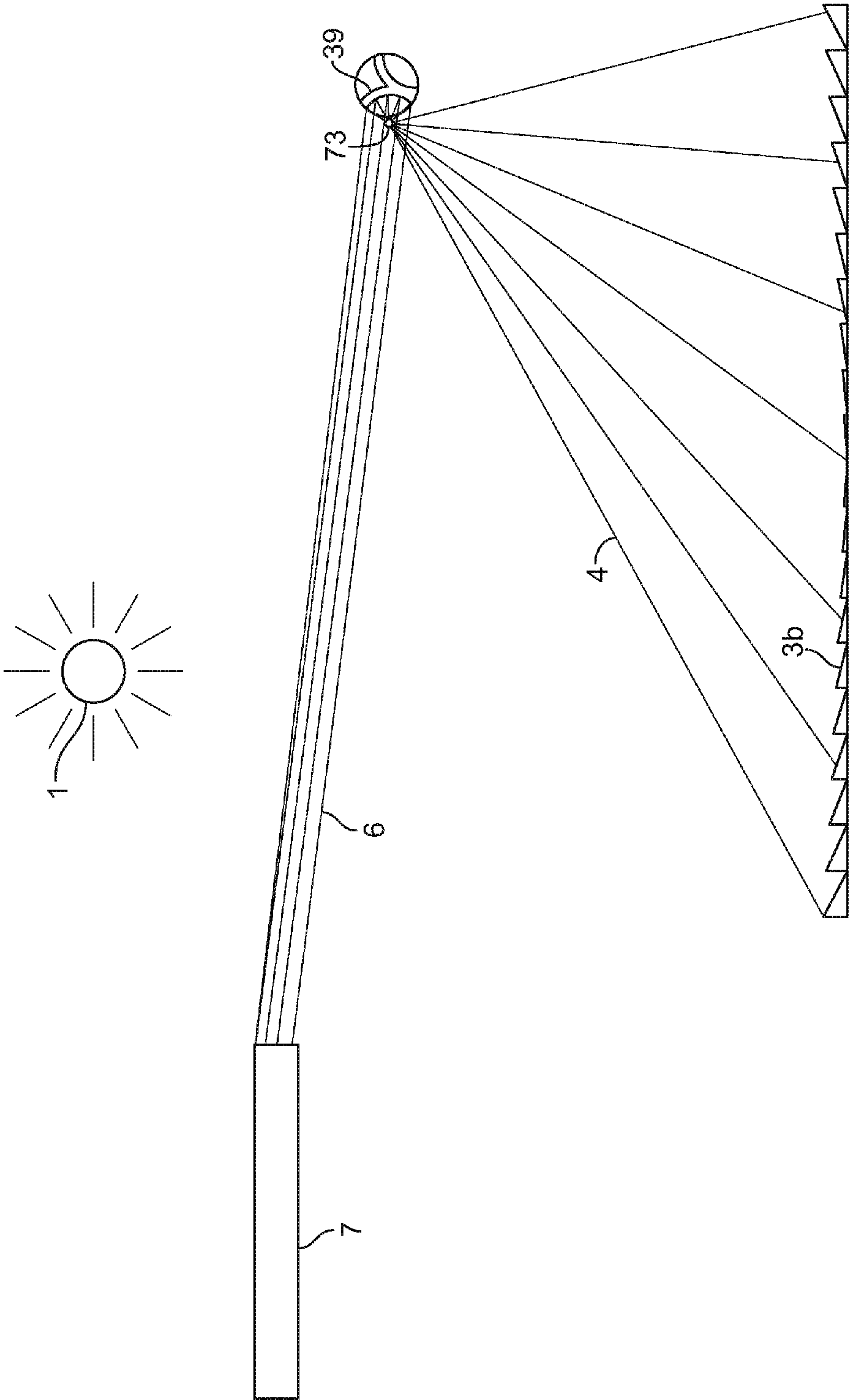


FIG. 16D

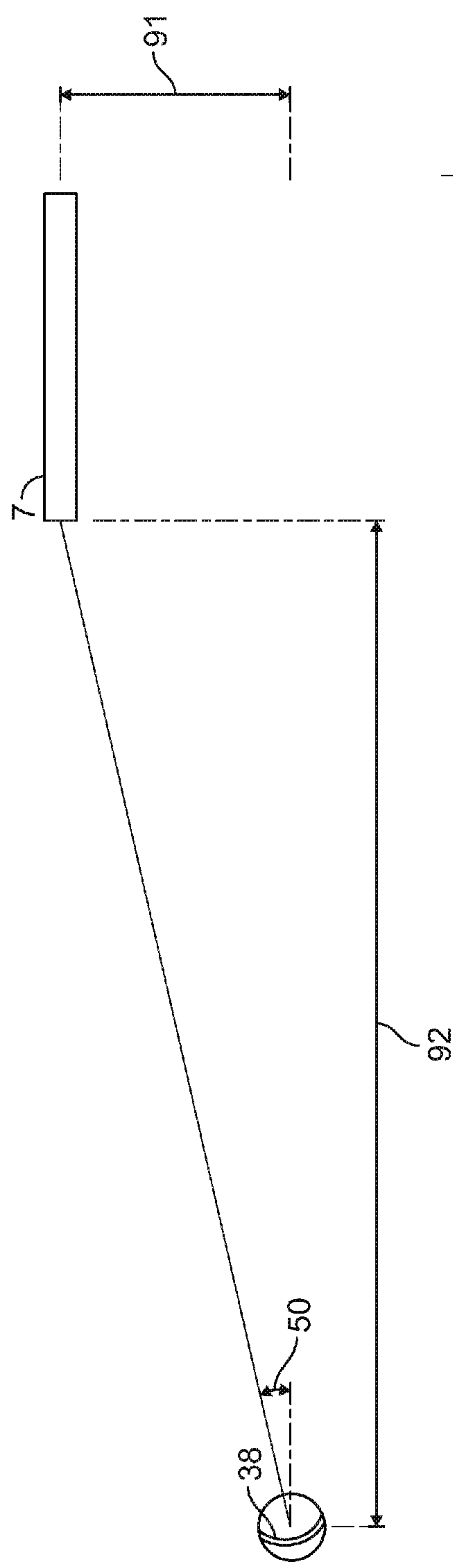


FIG. 17A

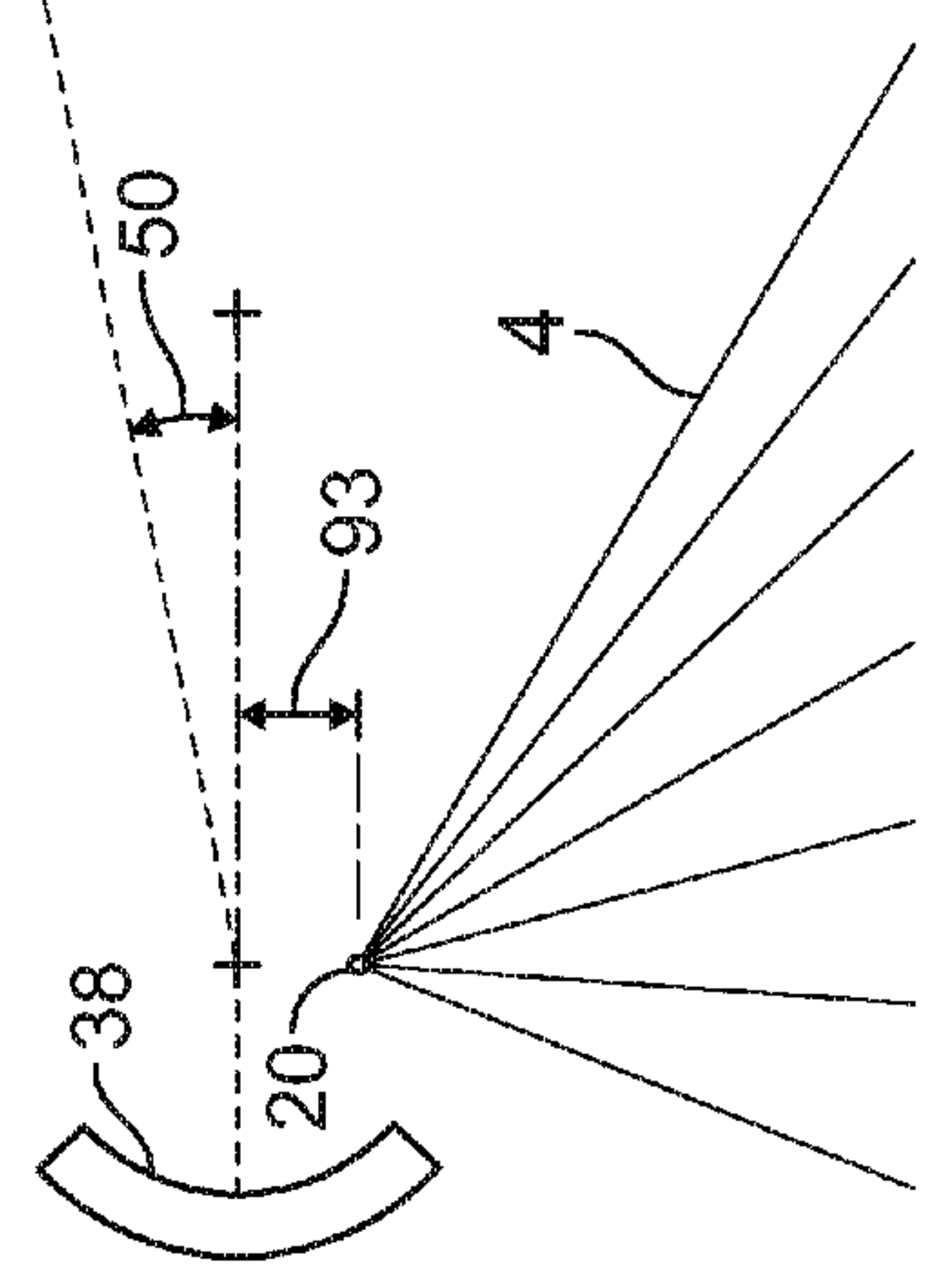
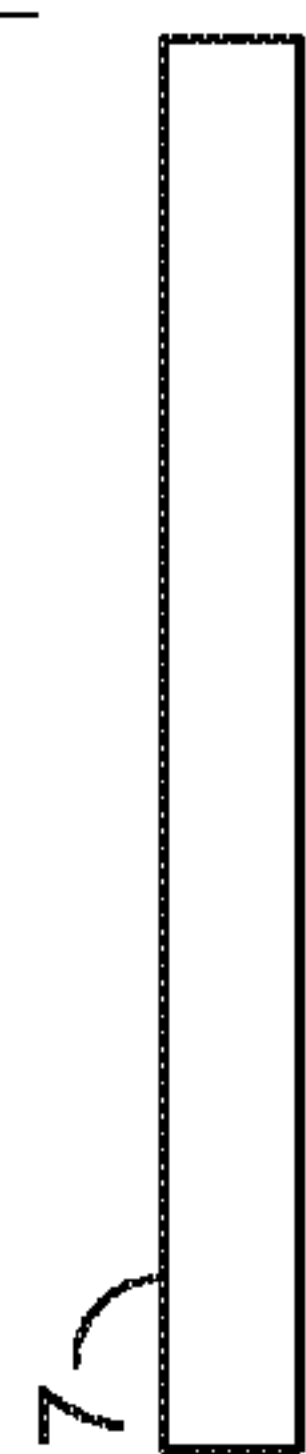
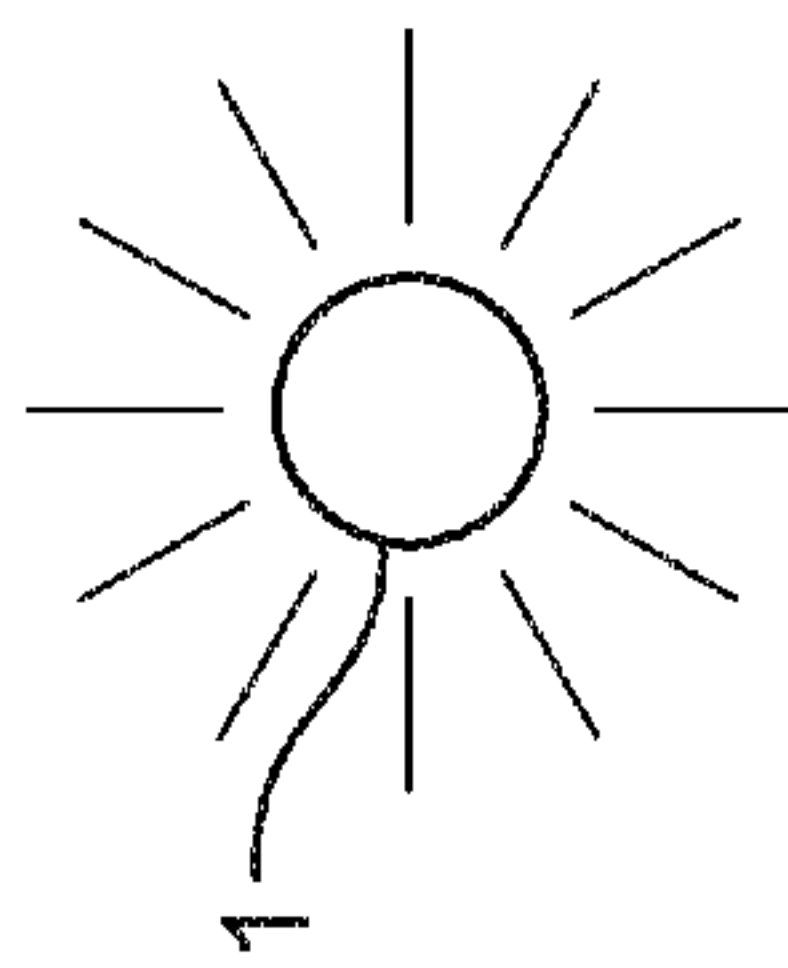


FIG. 17B

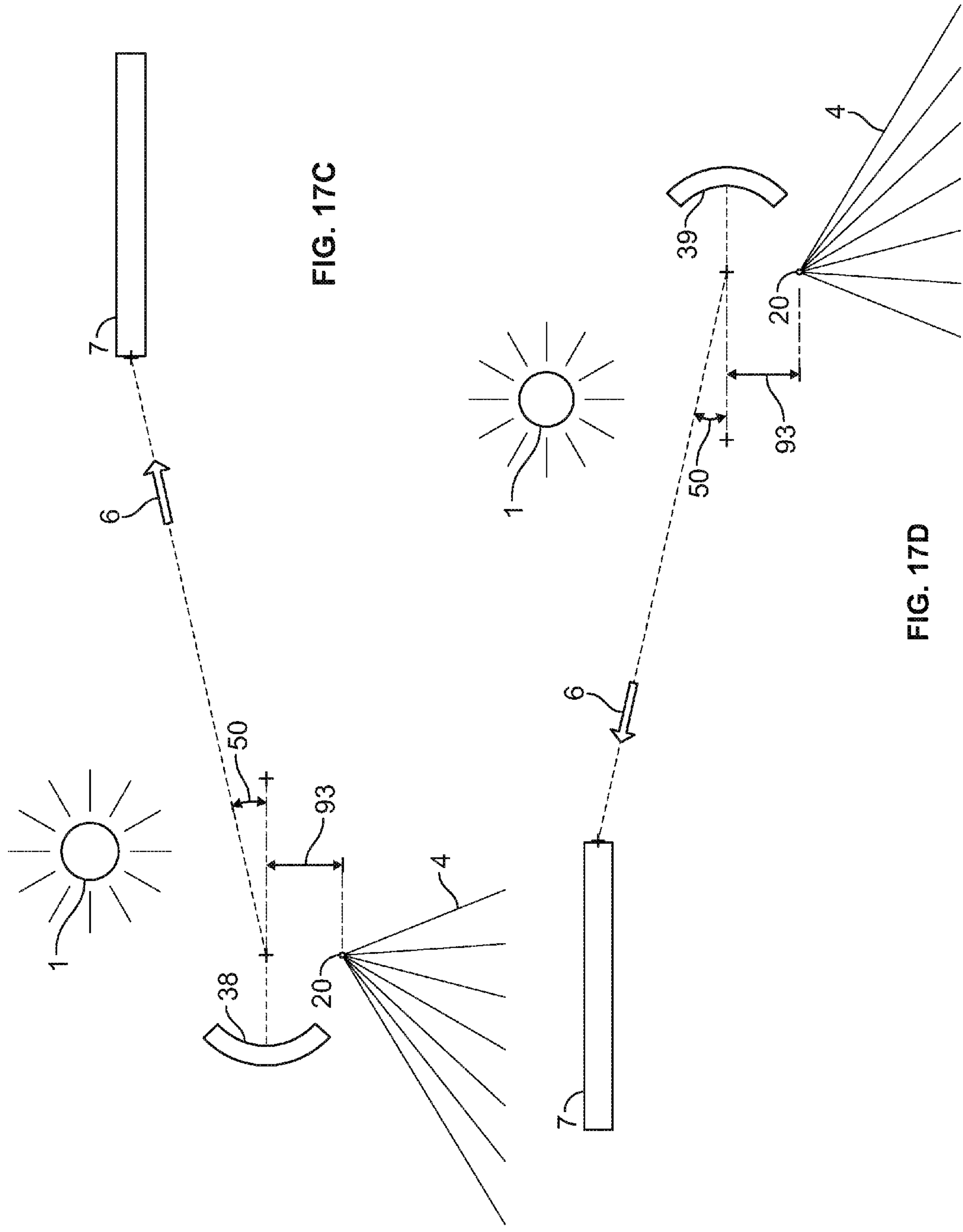
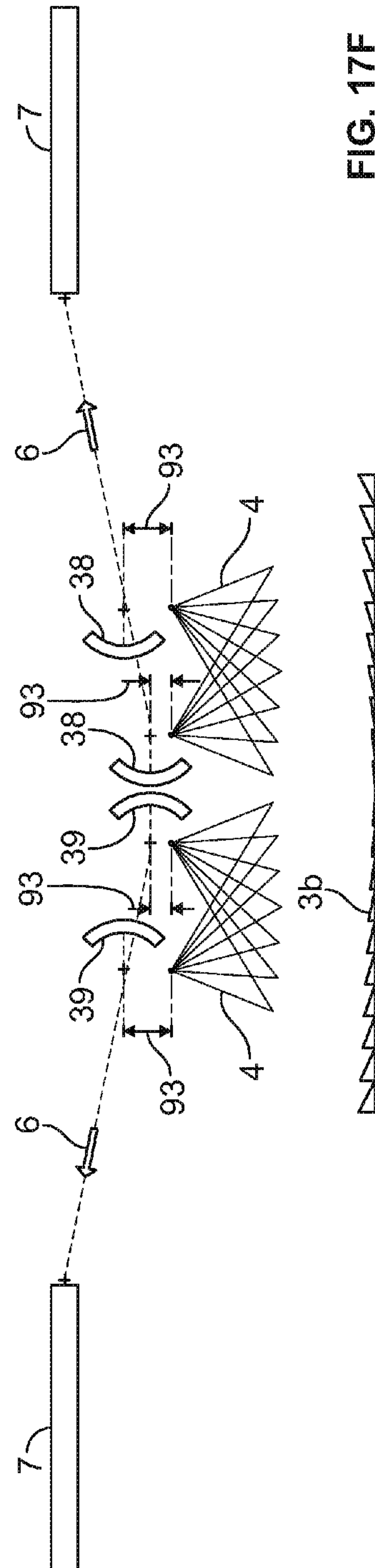
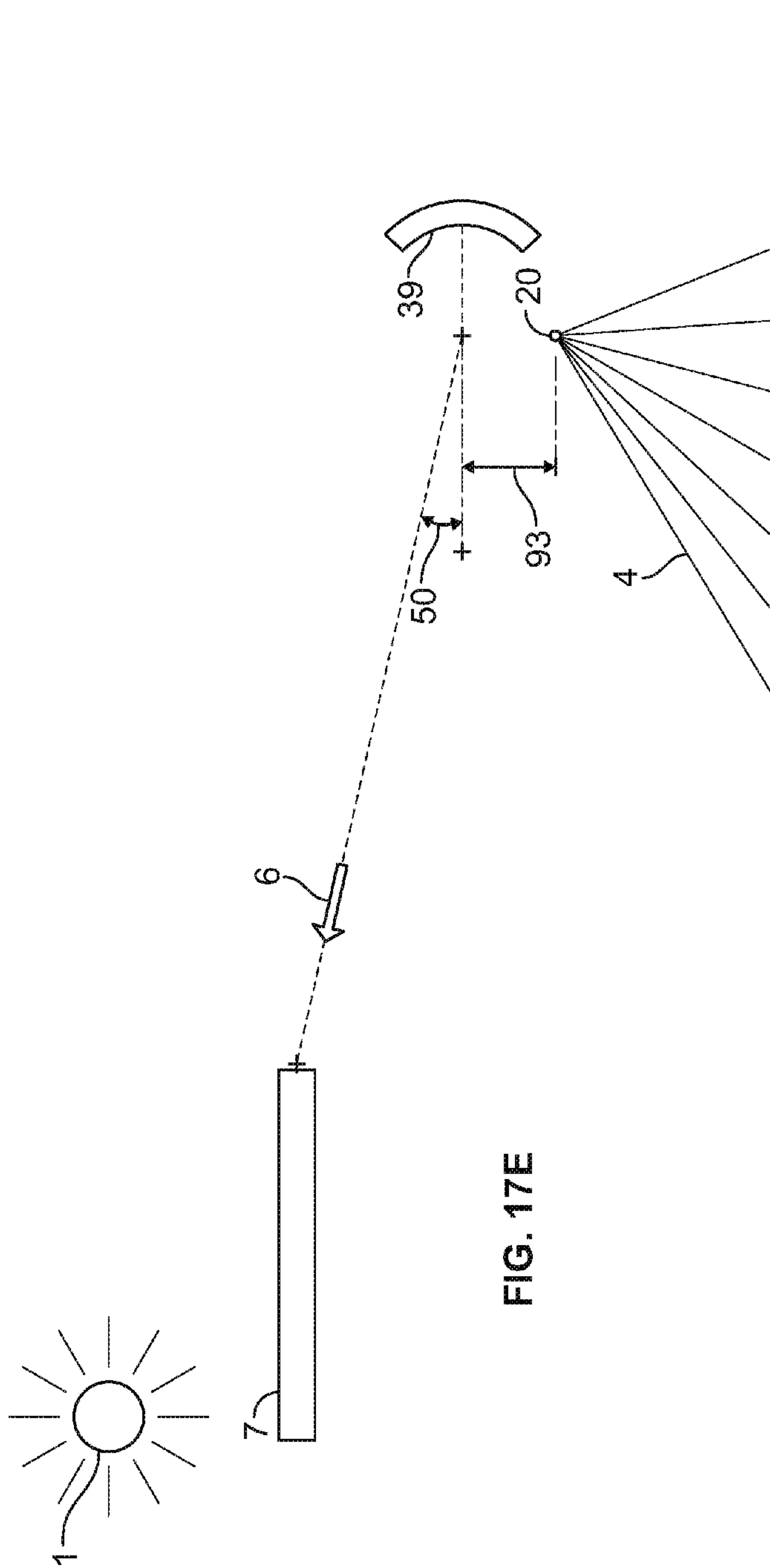


FIG. 17C

FIG. 17D



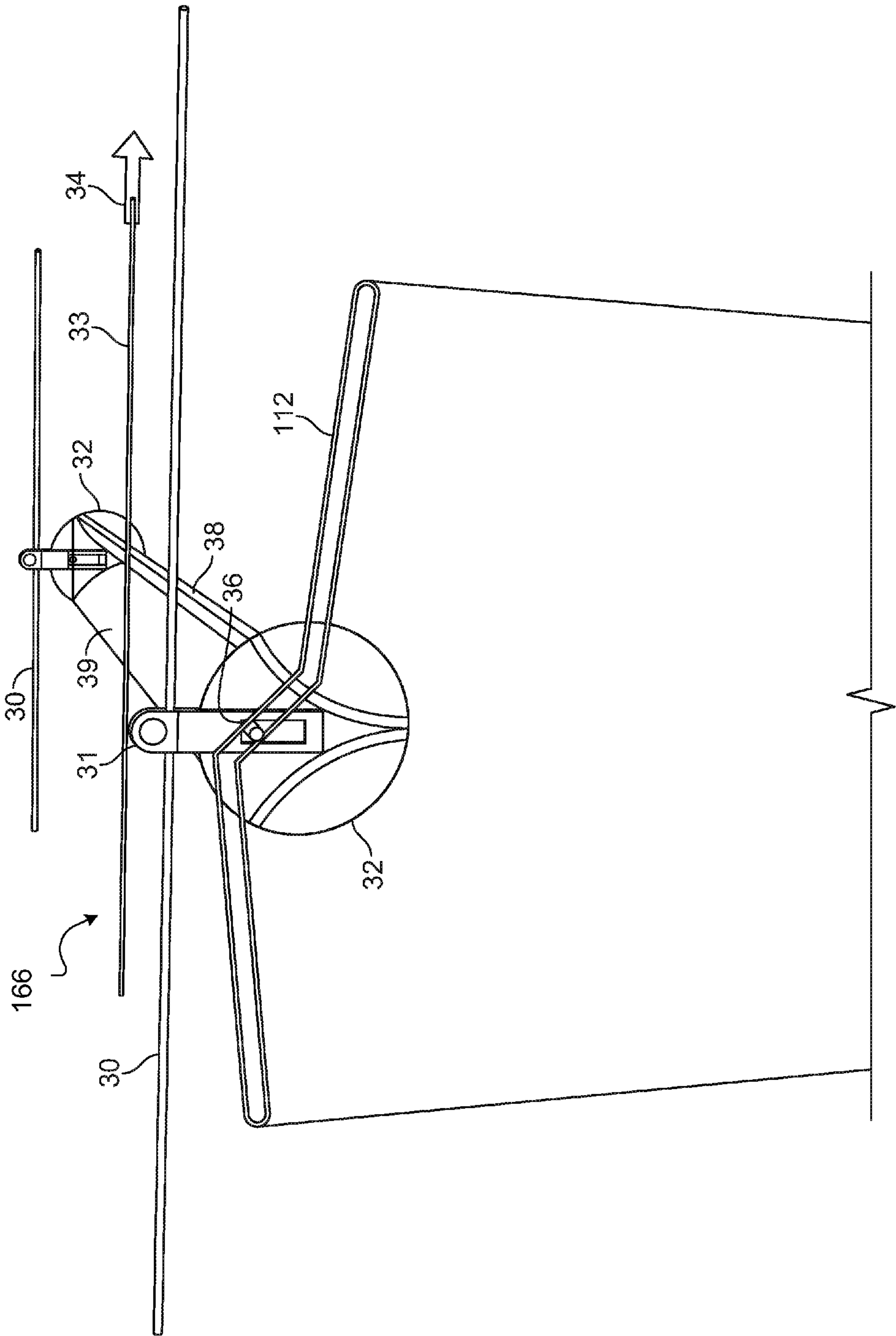


FIG. 17G

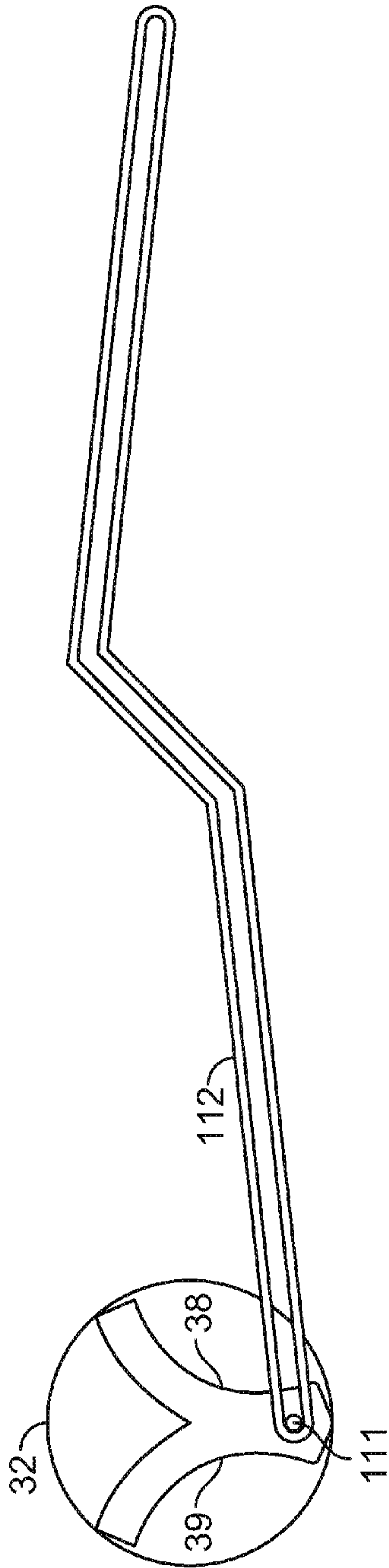


FIG. 17H

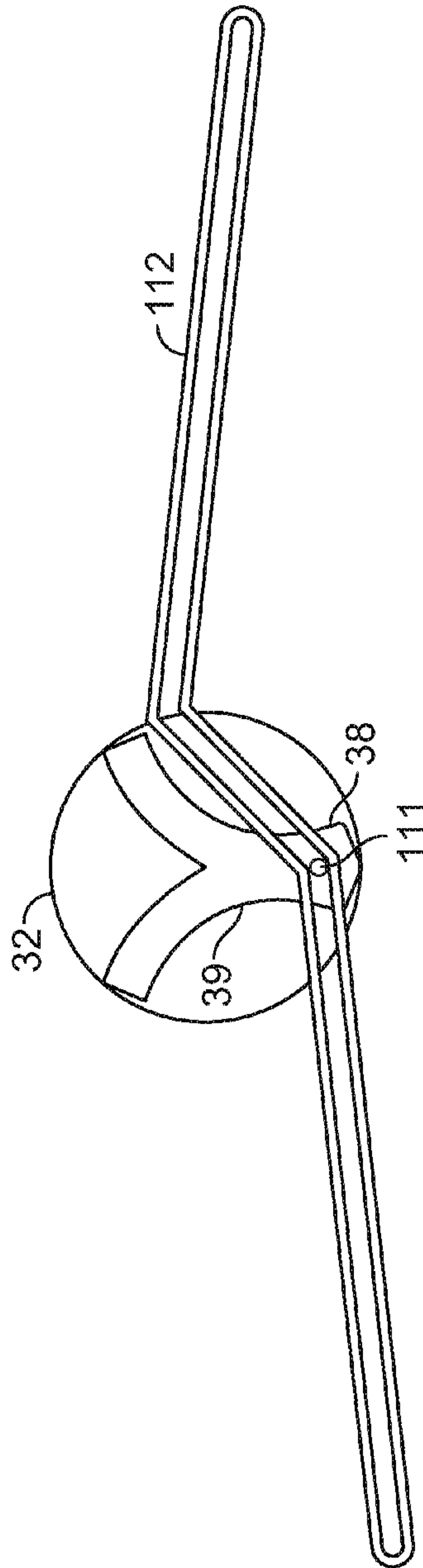


FIG. 17I

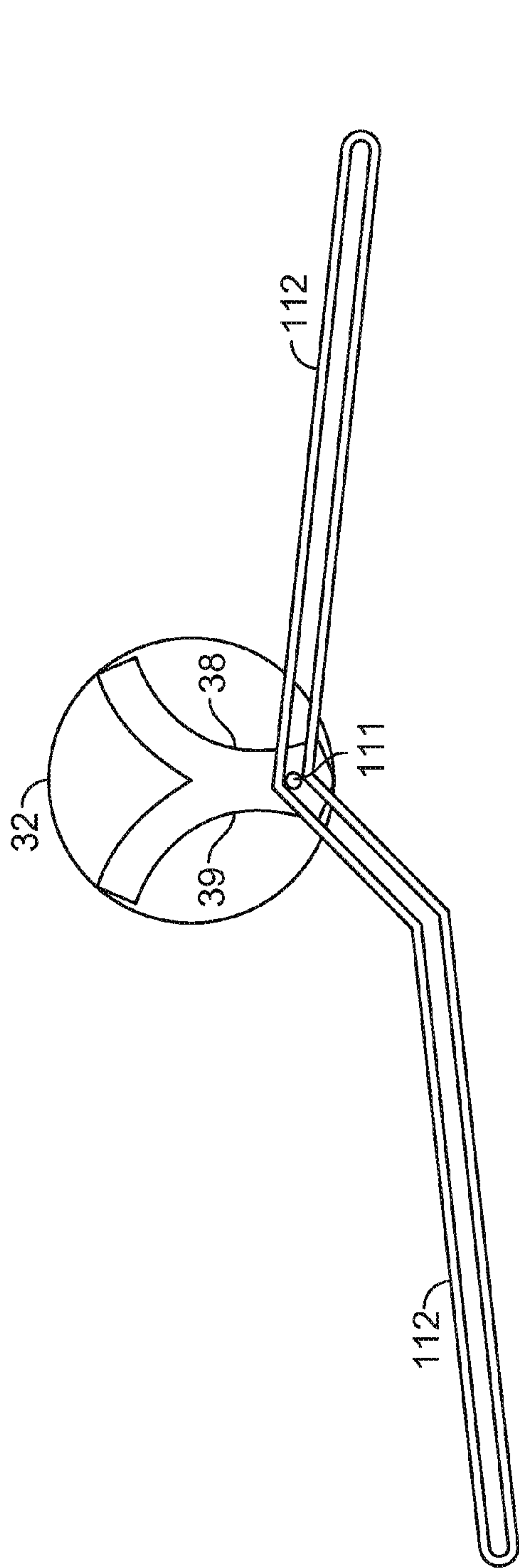


FIG. 17J

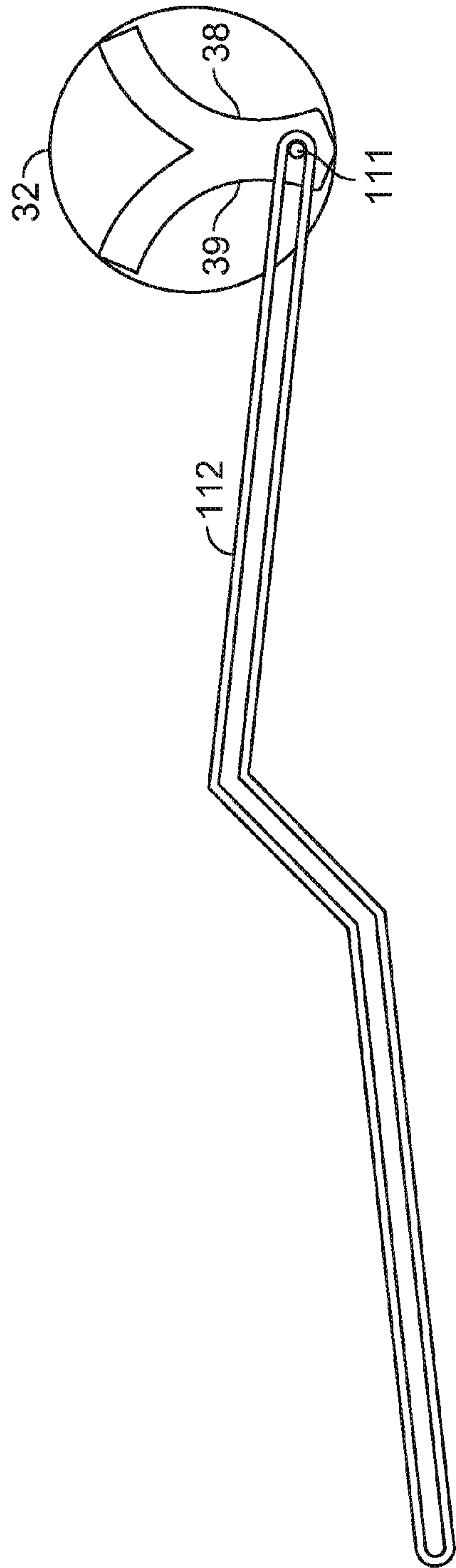


FIG. 17K

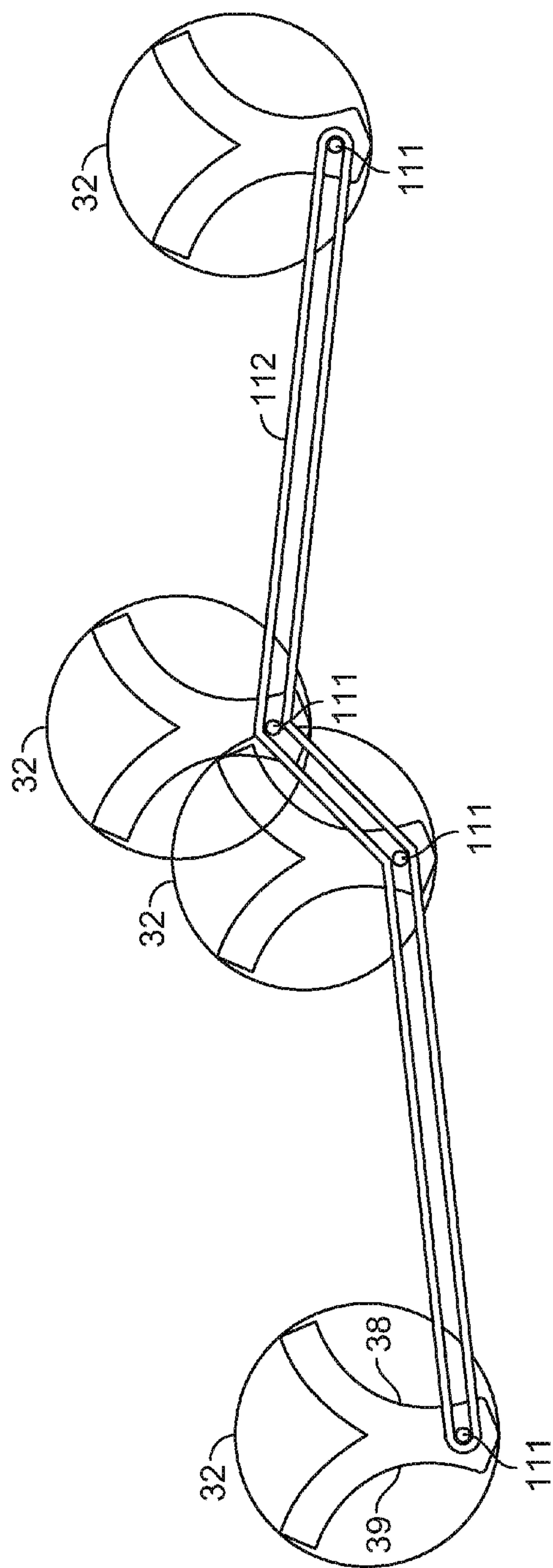


FIG. 17L

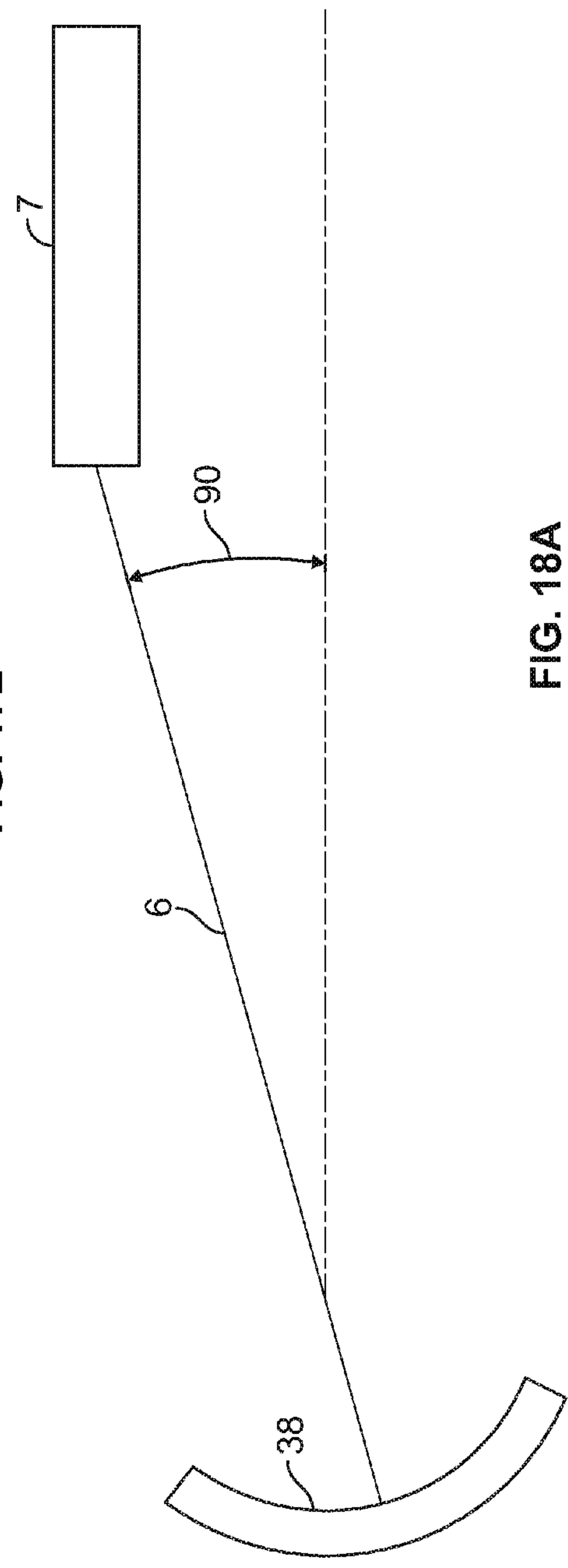
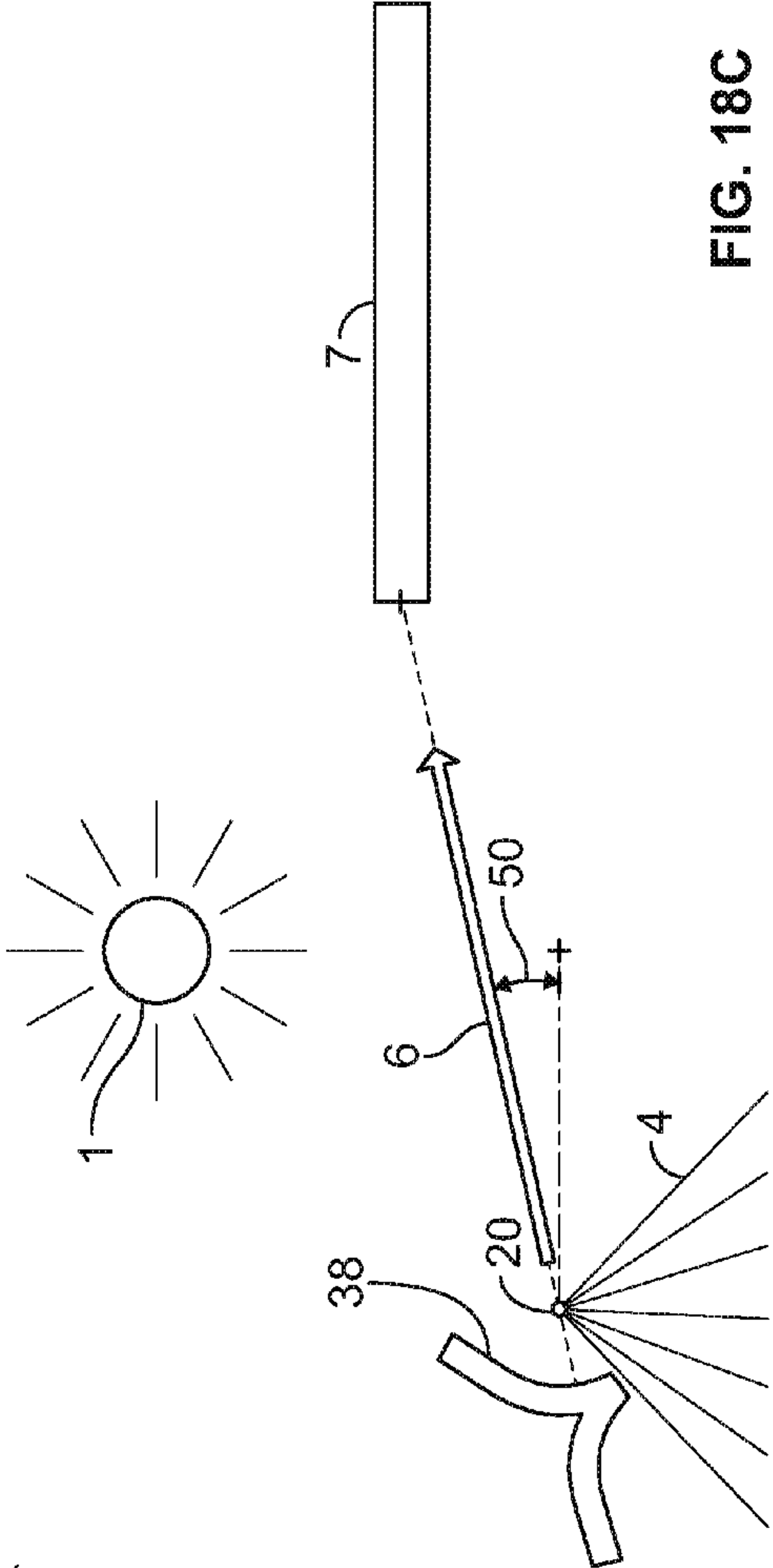
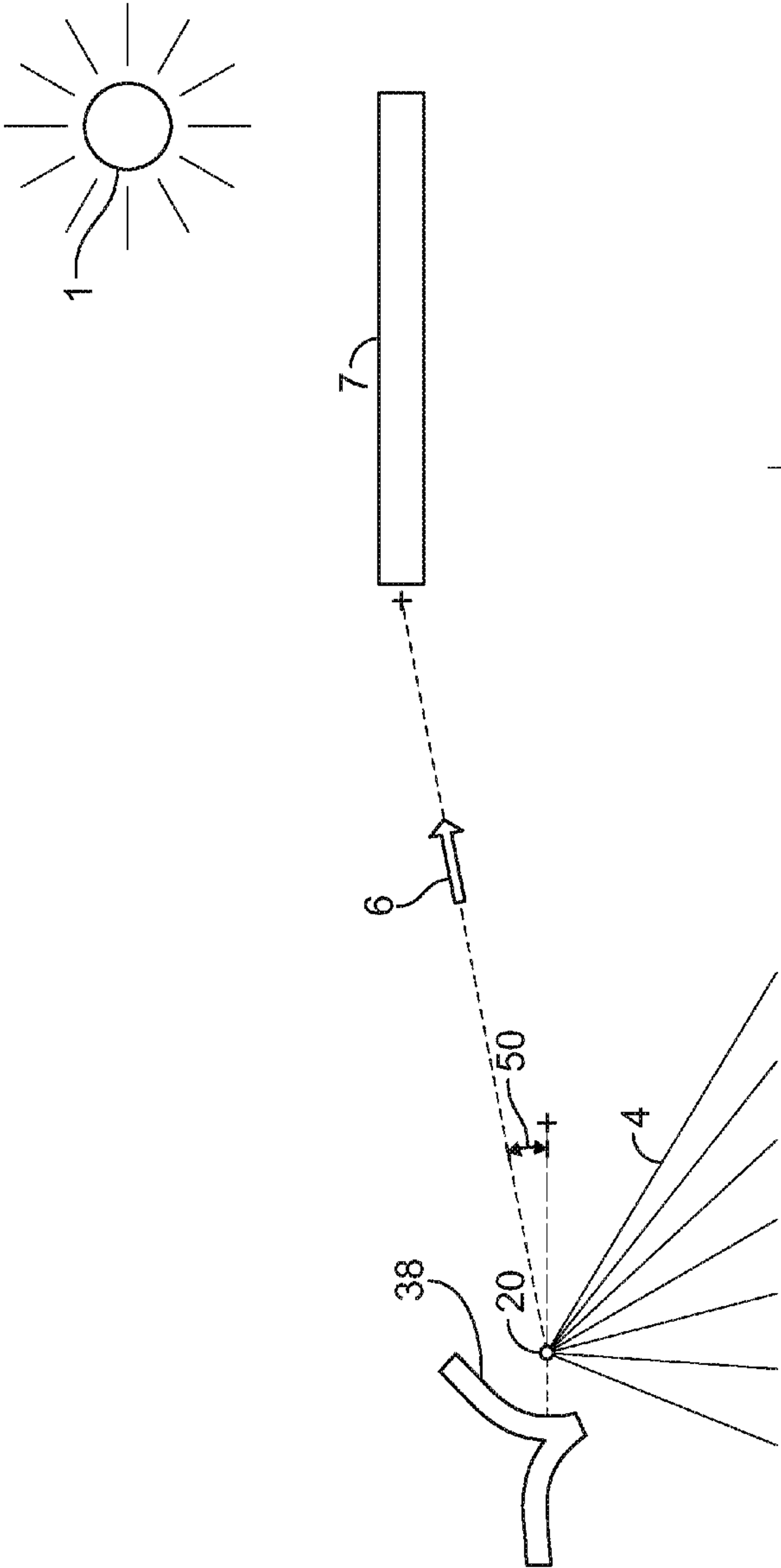
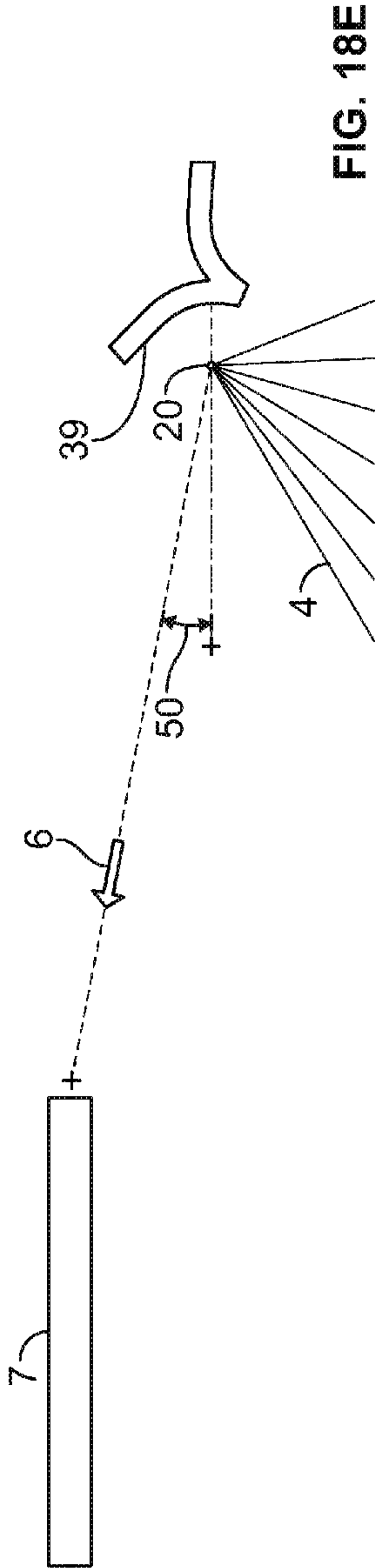
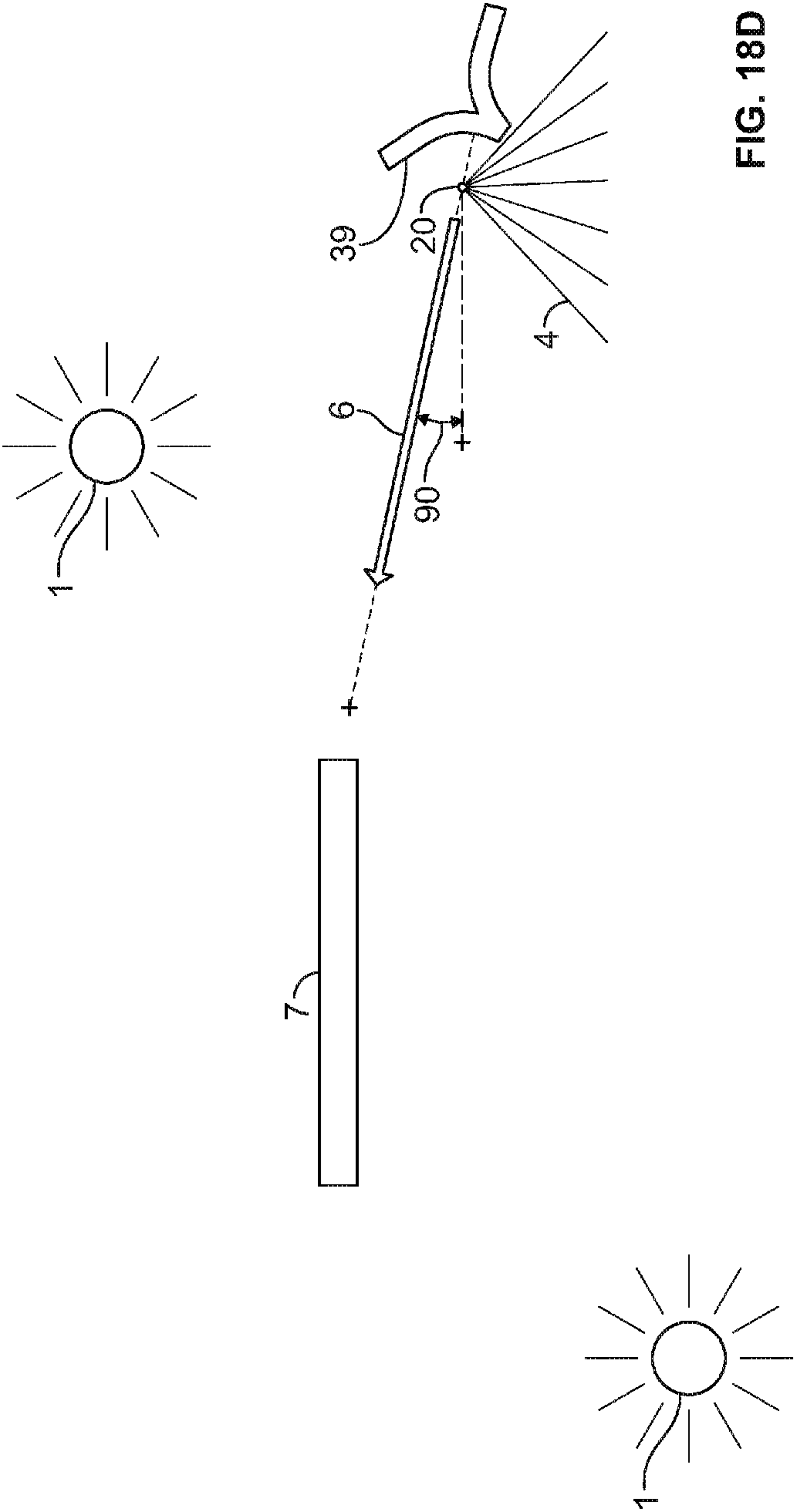


FIG. 18A





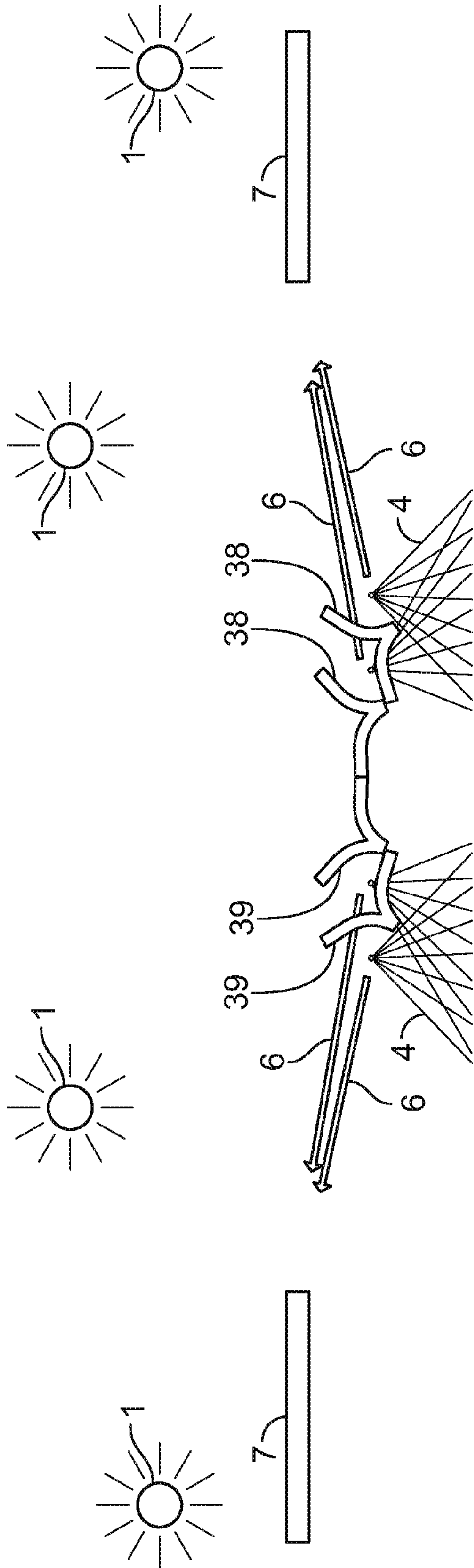


FIG. 18F

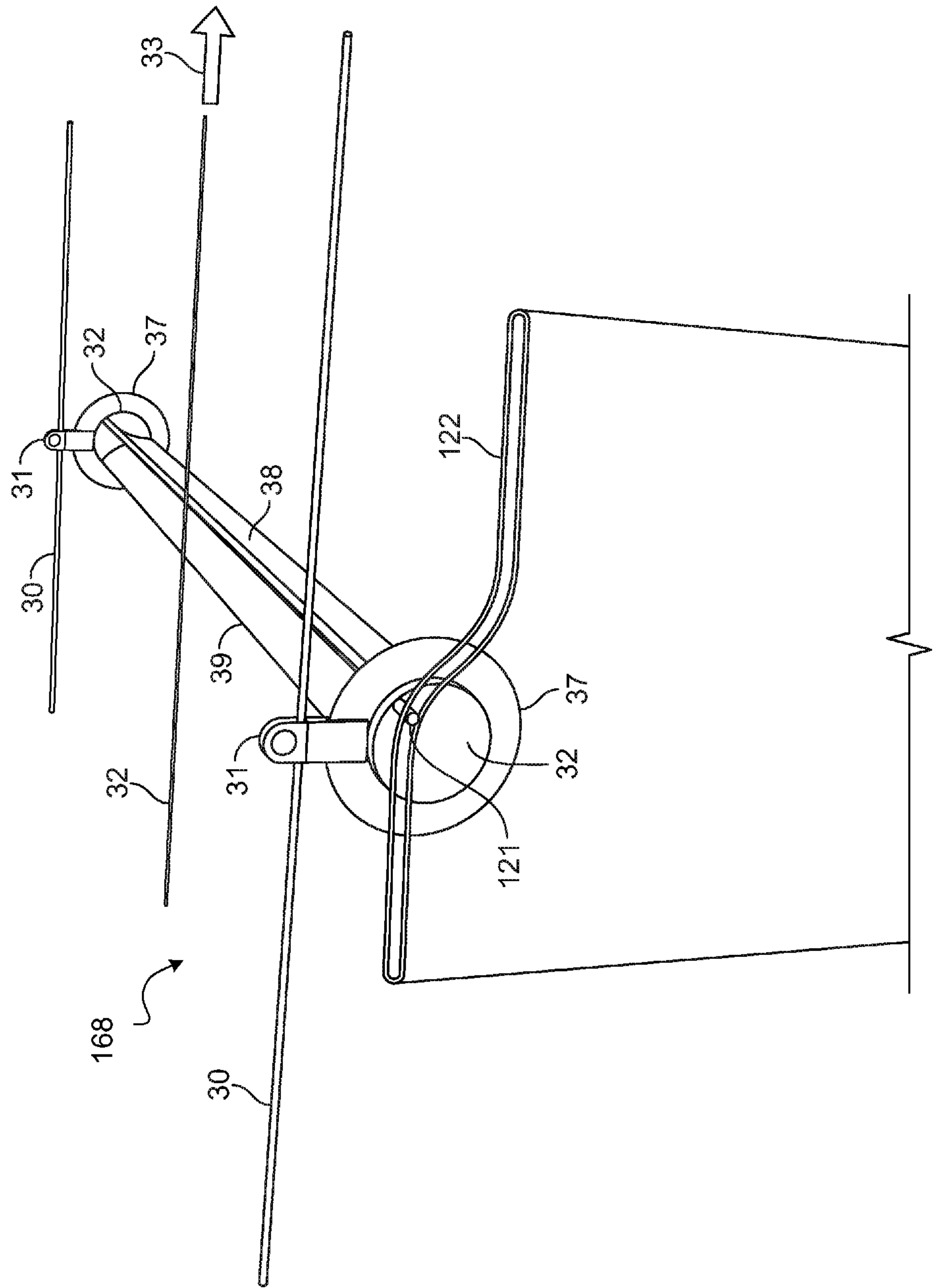
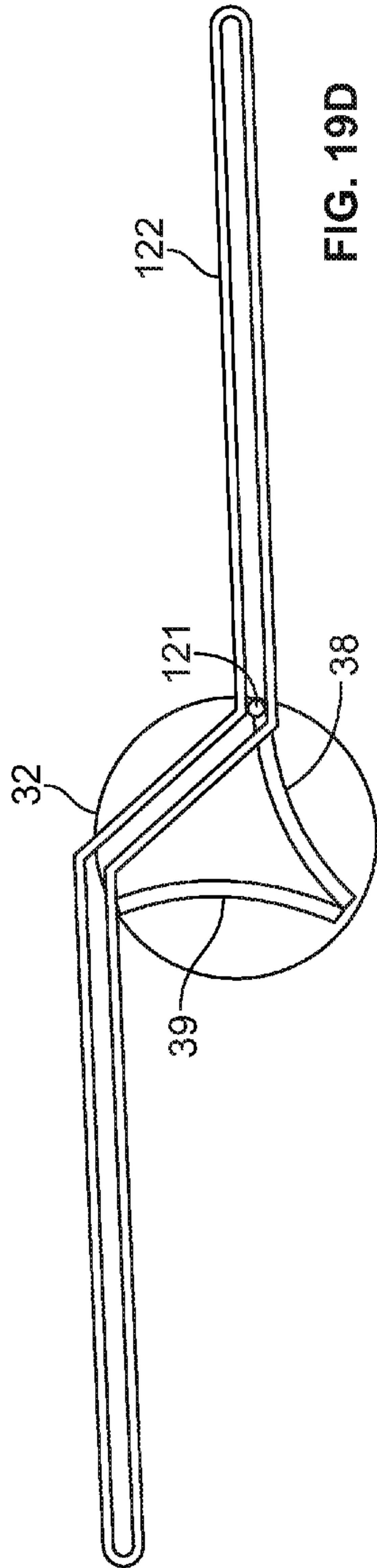
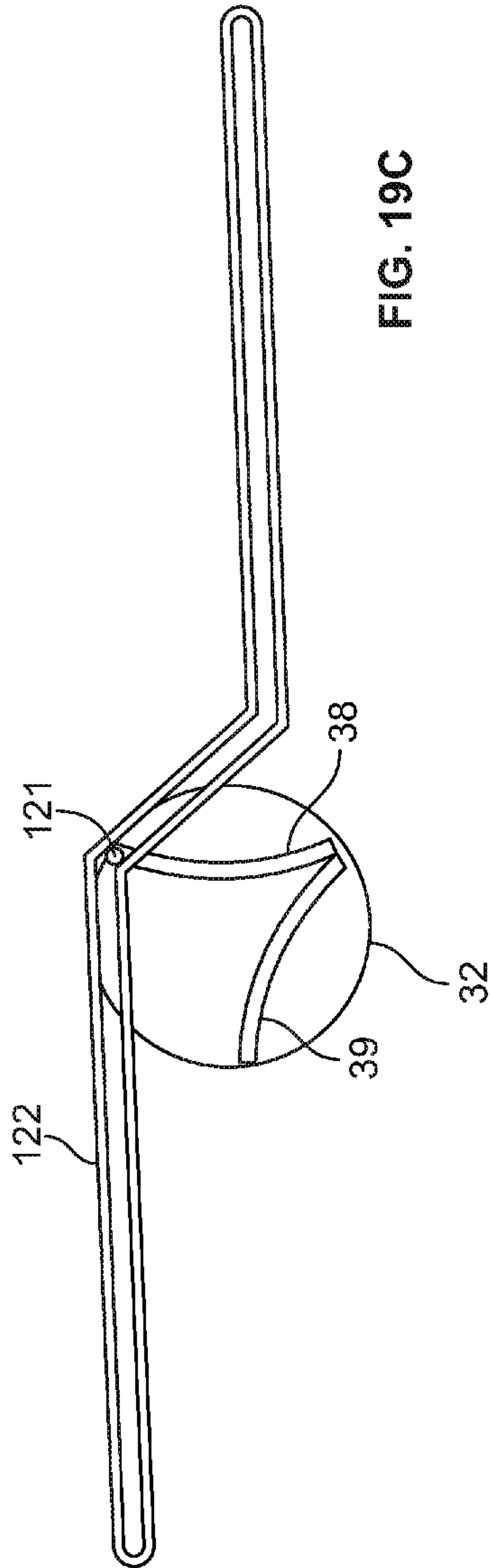
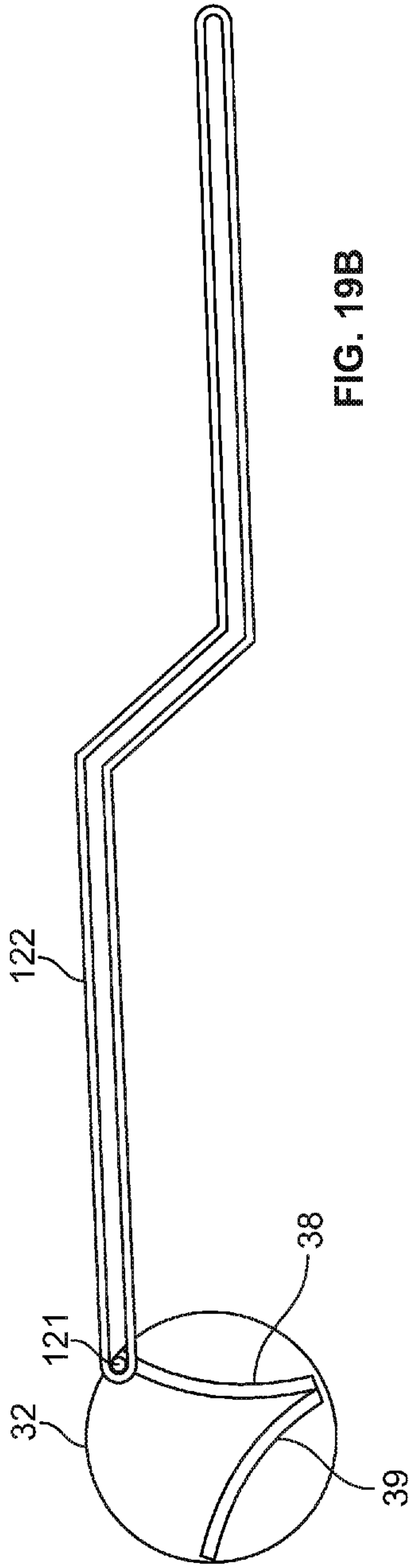
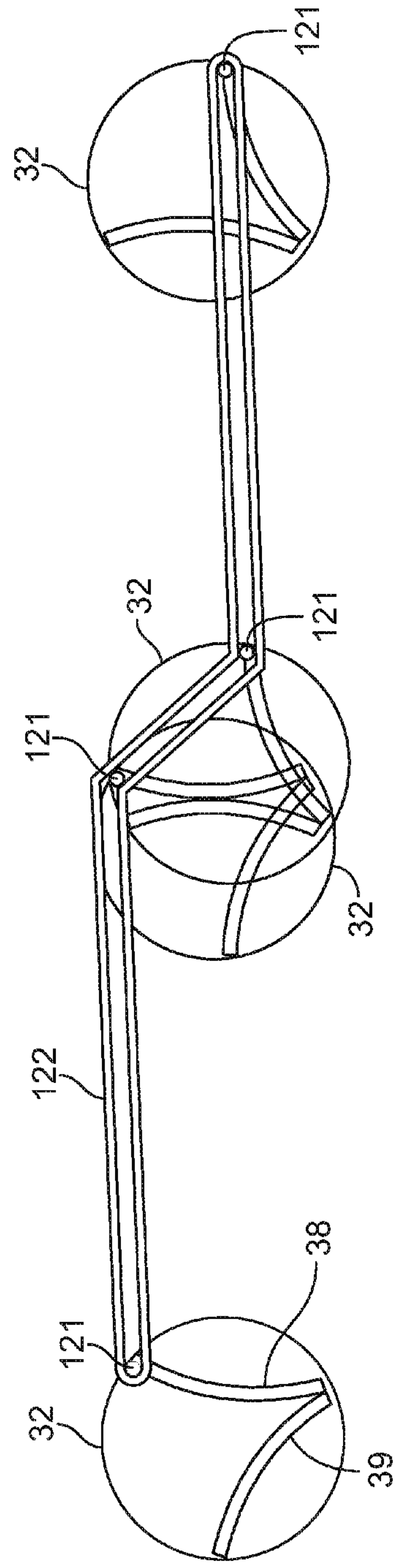
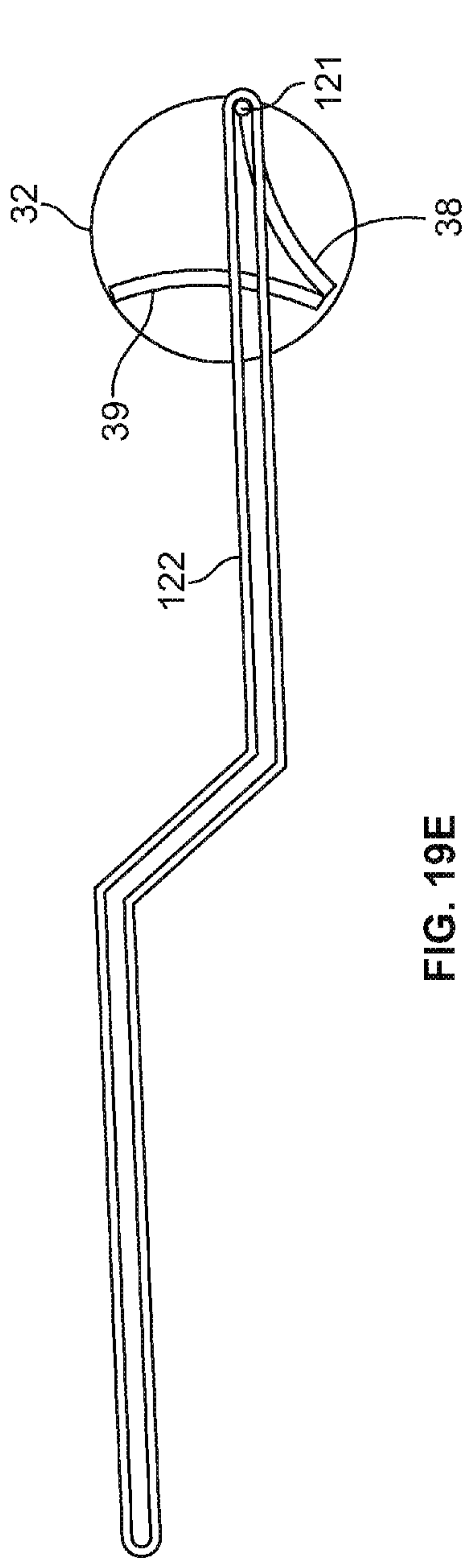


FIG. 19A





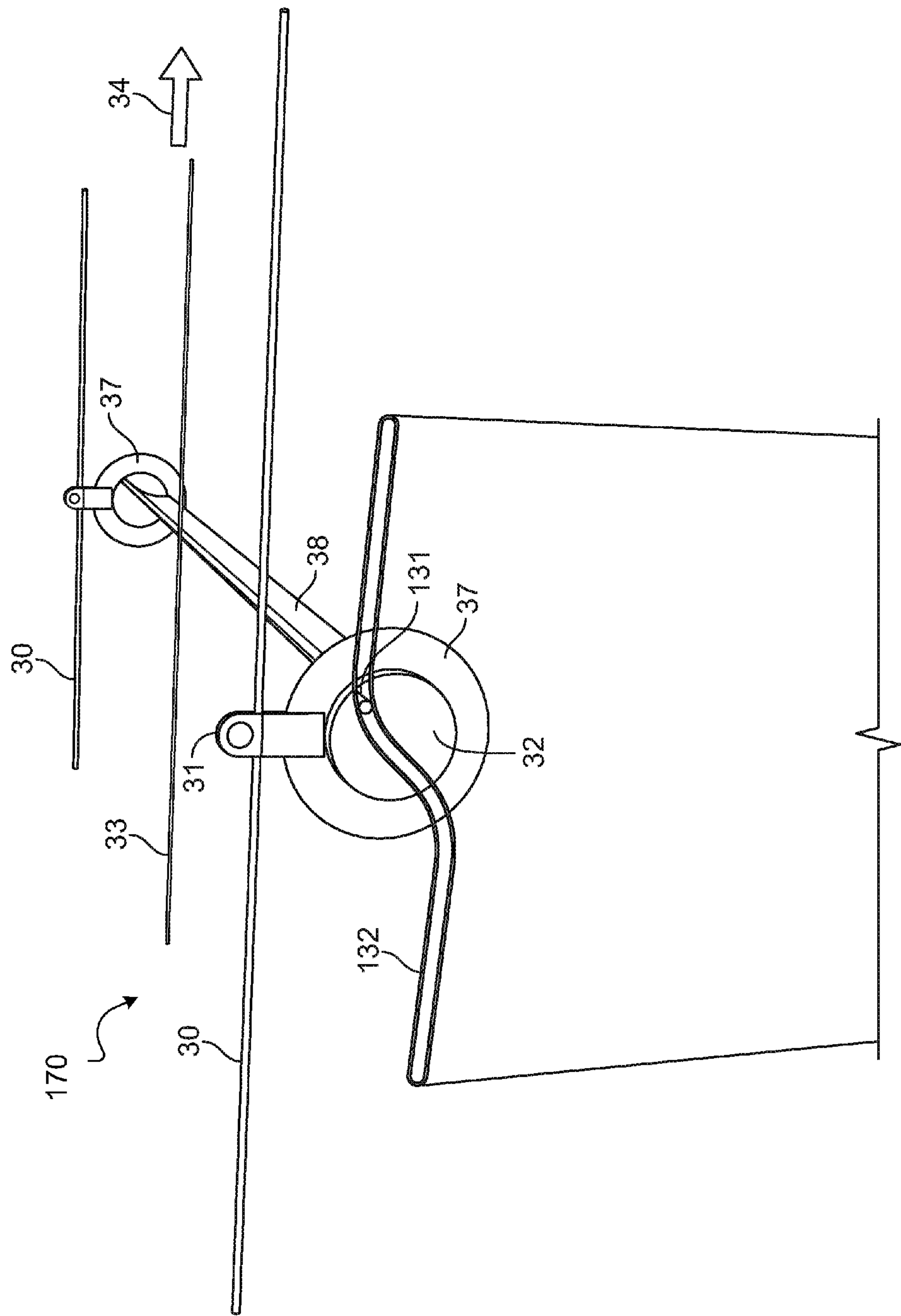


FIG. 20A

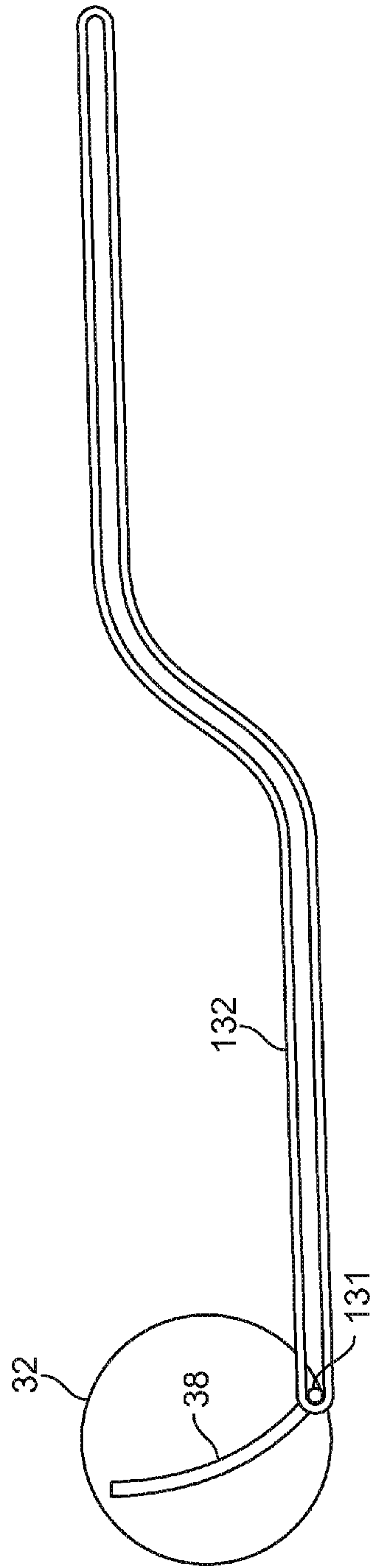


FIG. 20B

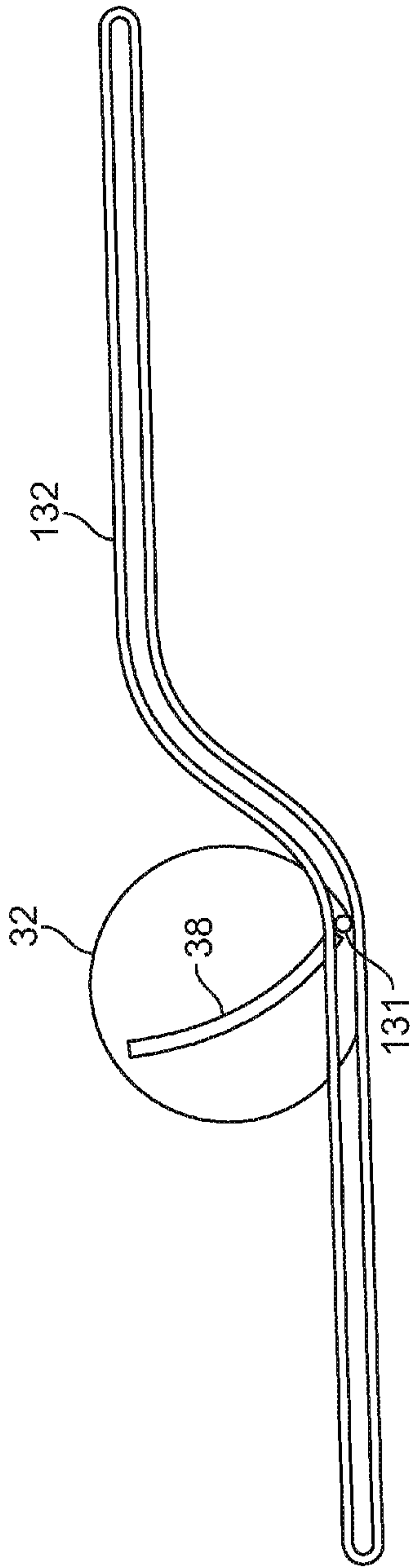


FIG. 20C

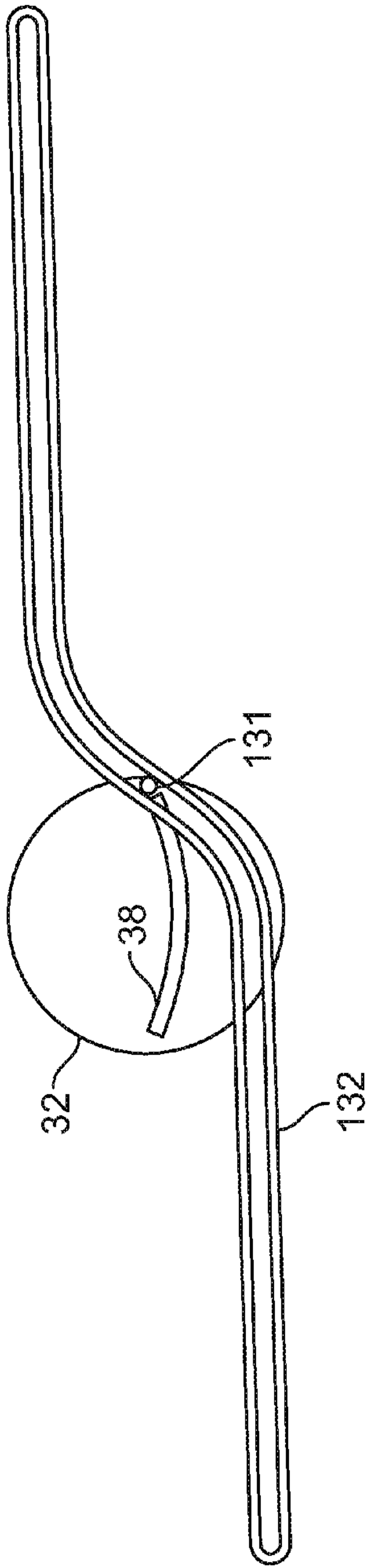


FIG. 20D

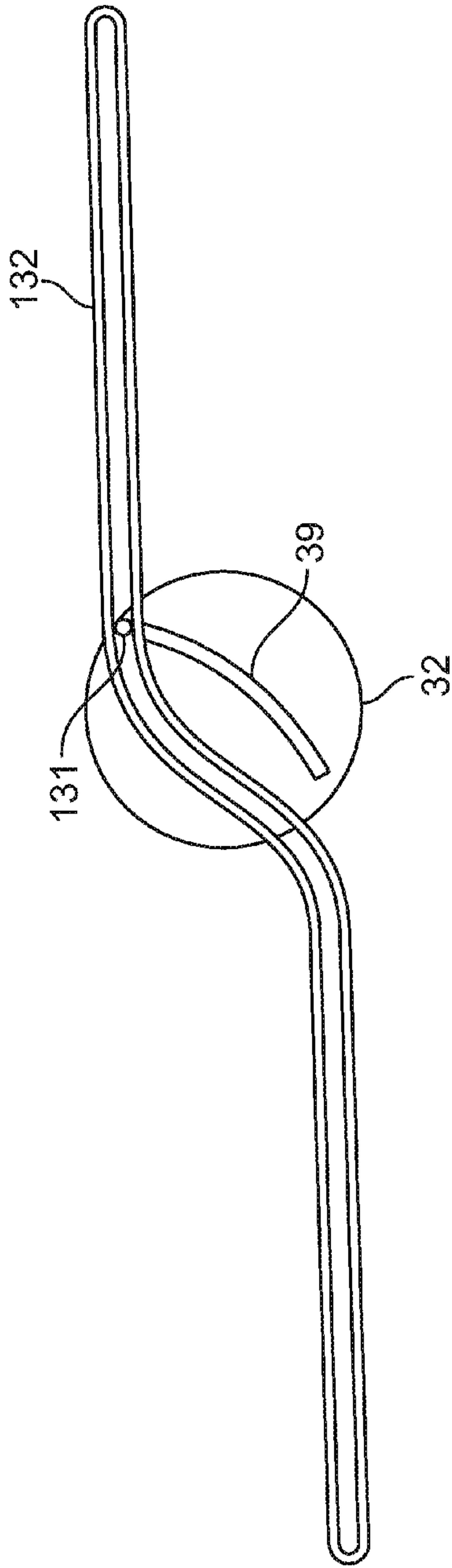


FIG. 20E

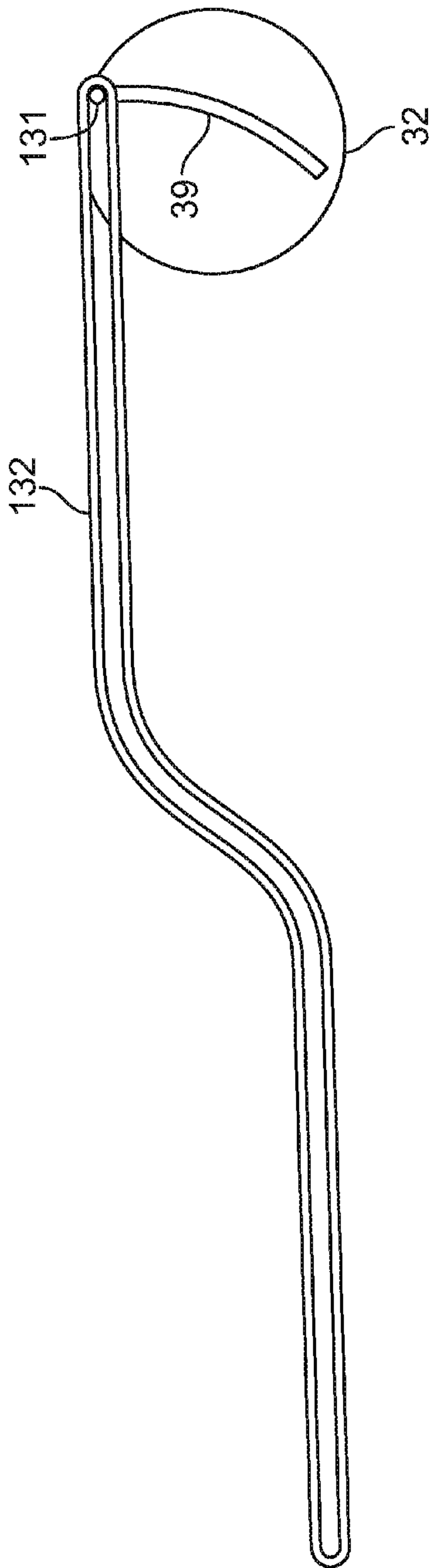


FIG. 20F

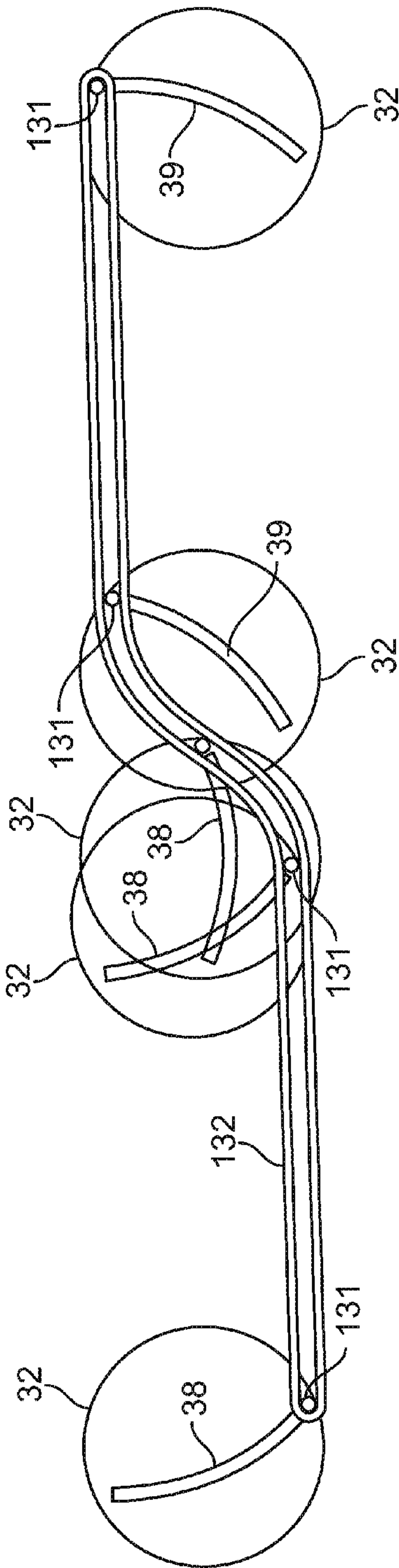
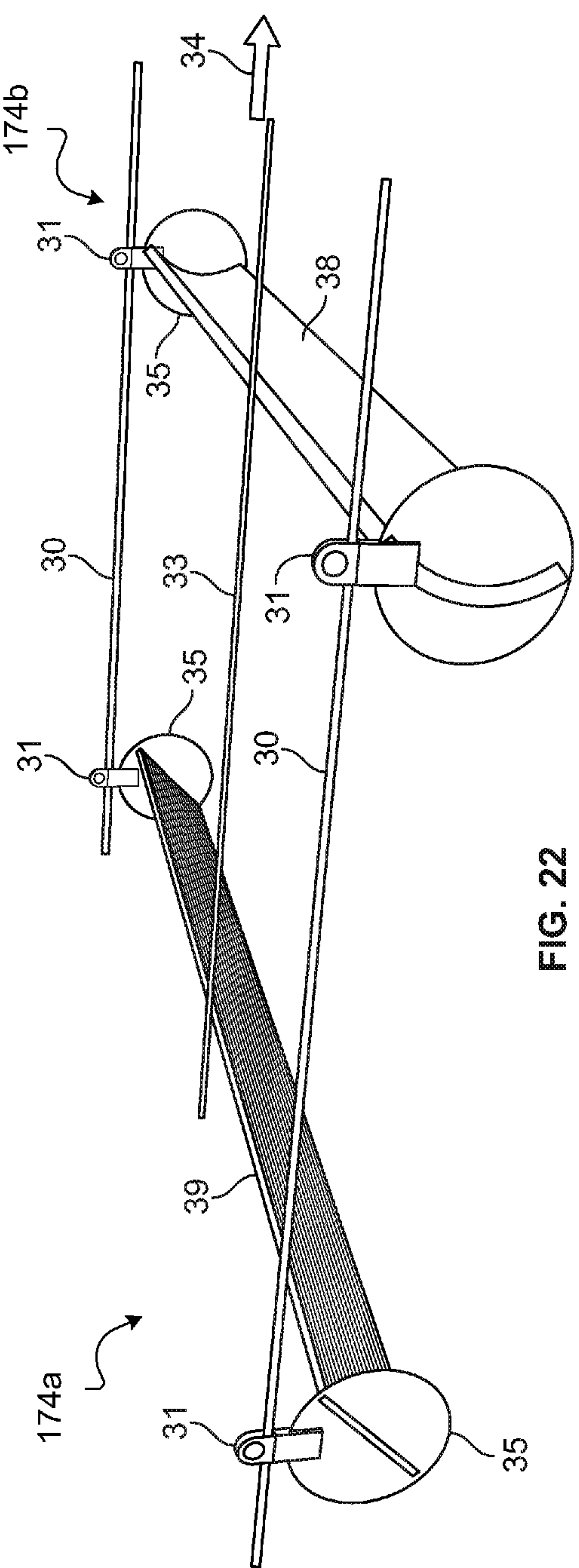
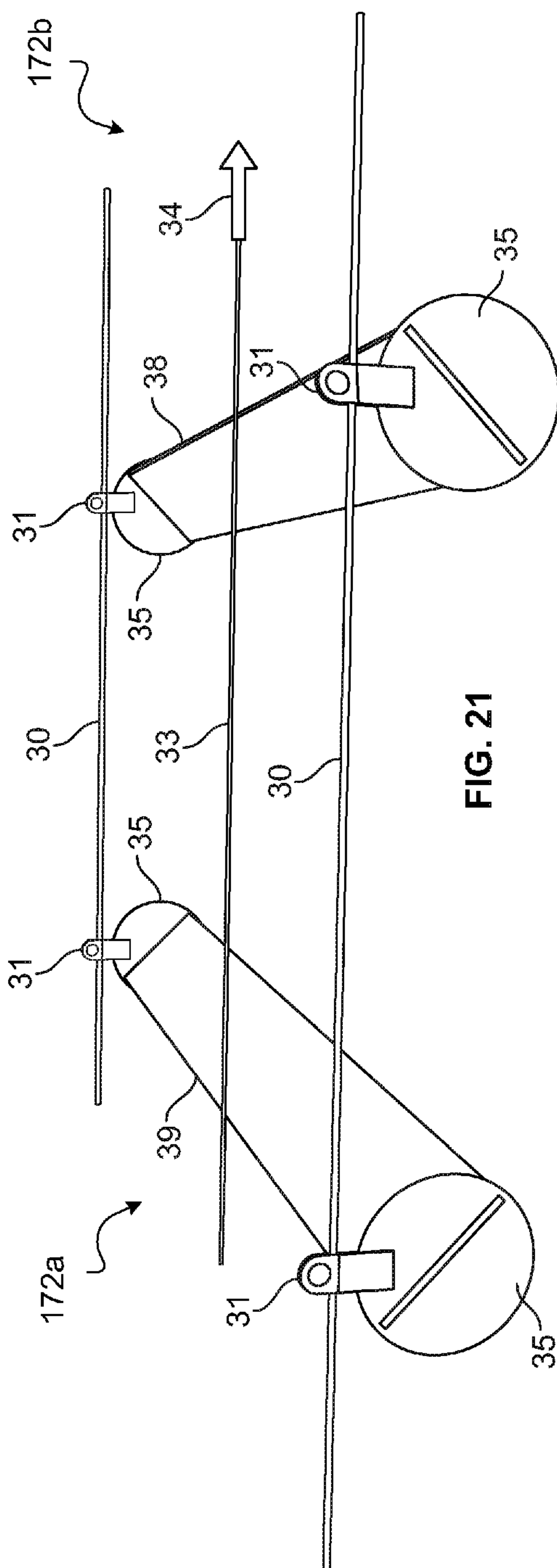


FIG. 20G



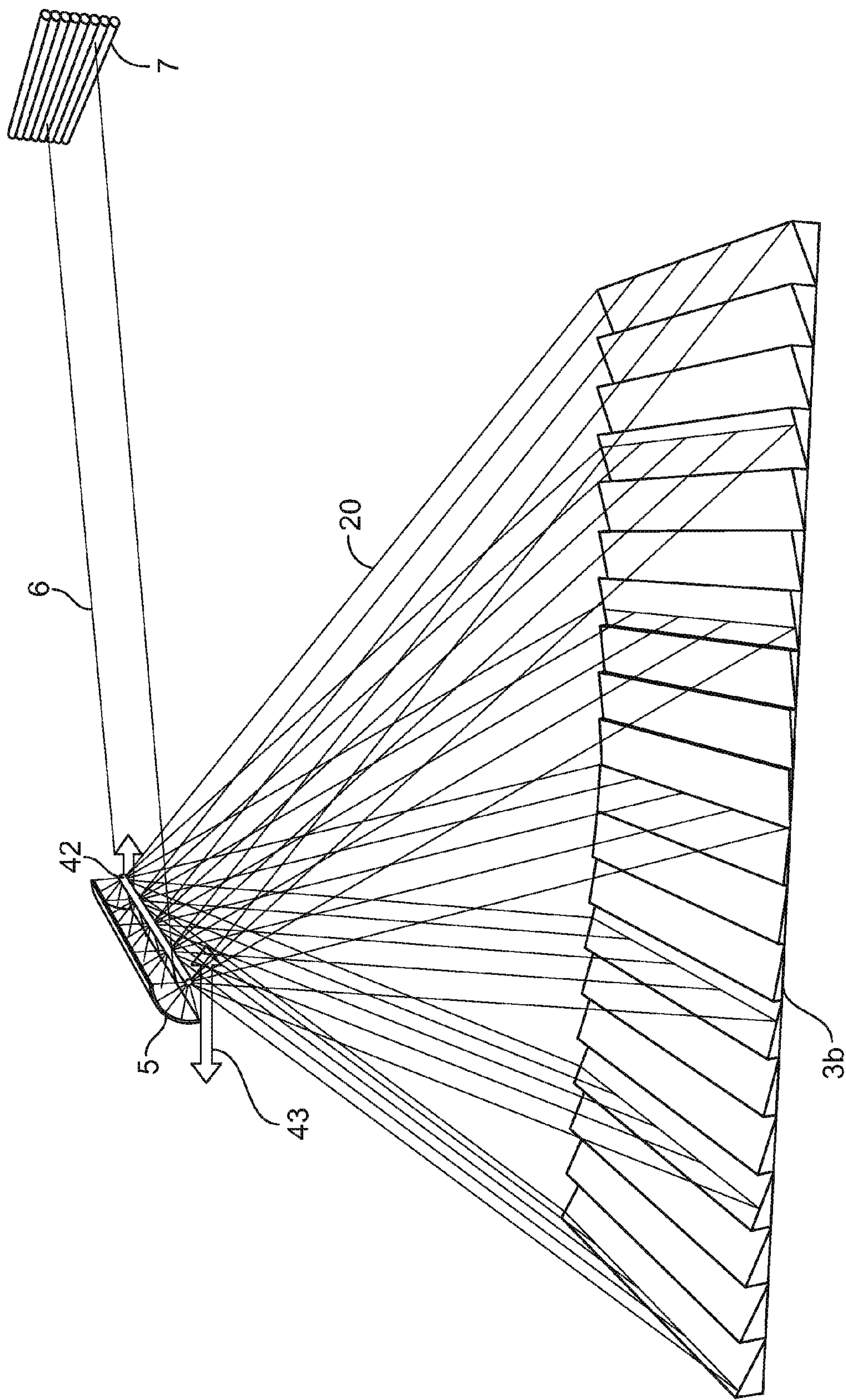


FIG. 23A

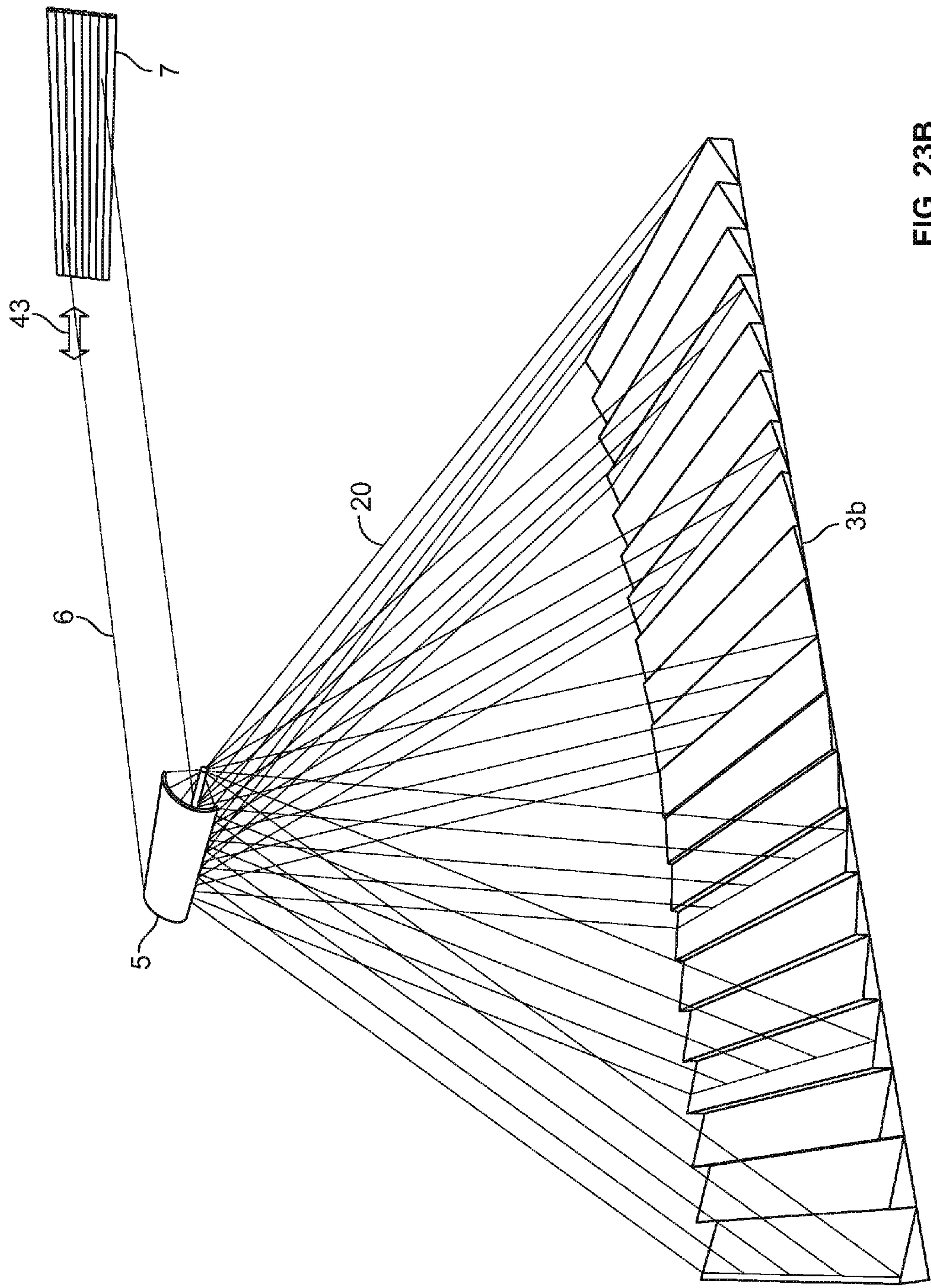


FIG. 23B

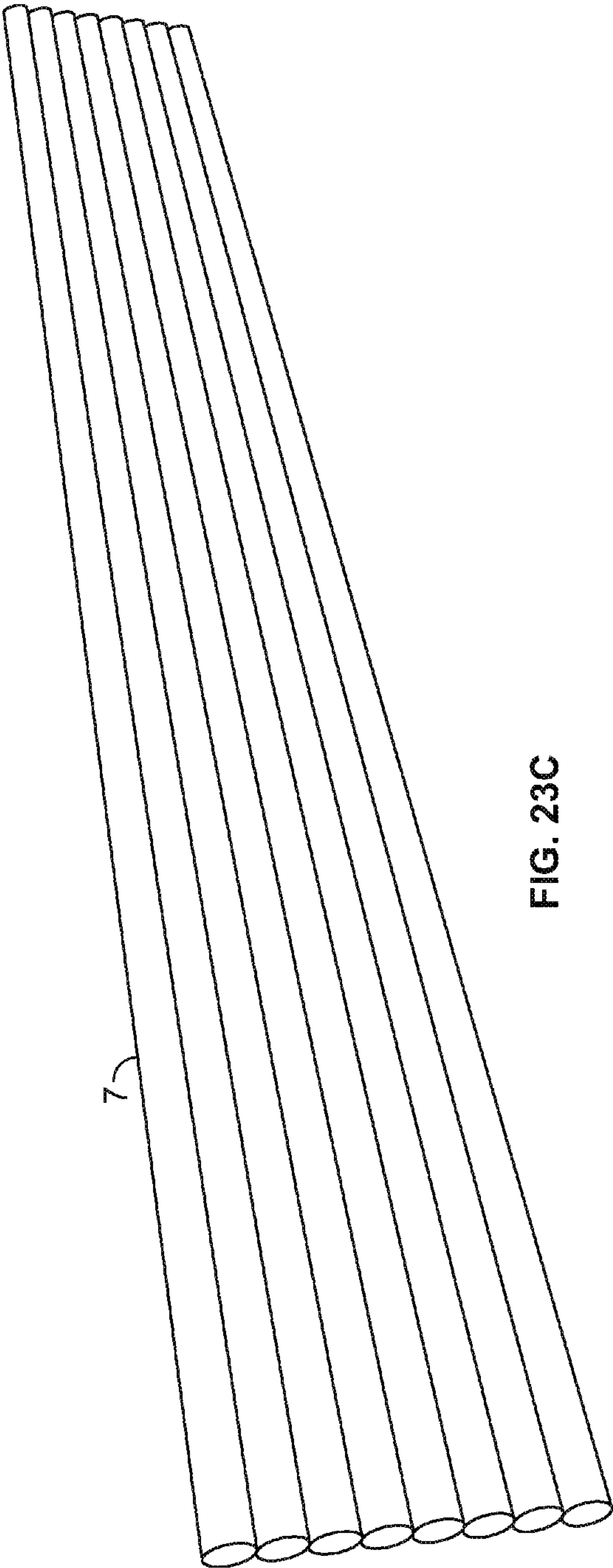


FIG. 23C

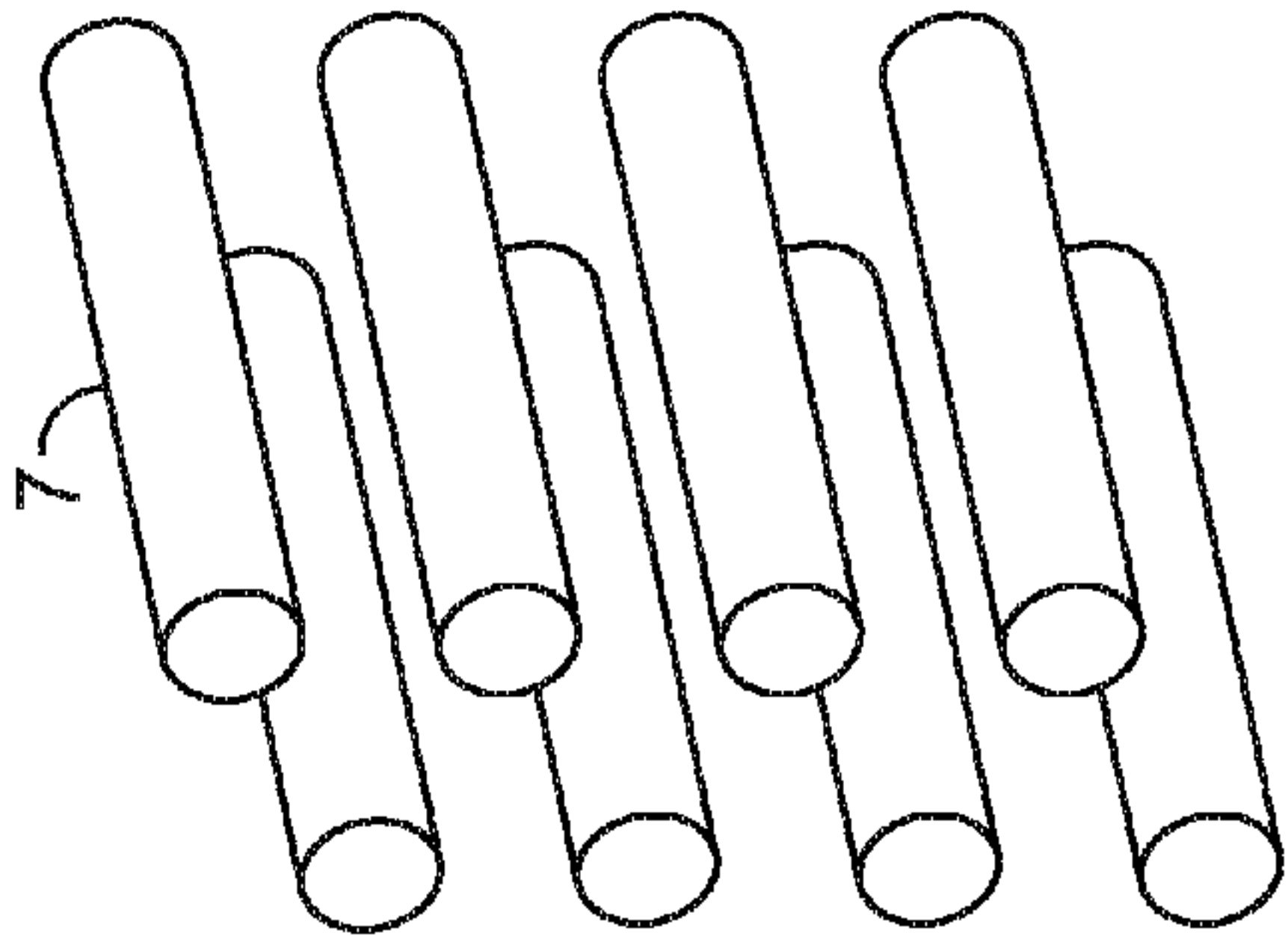


FIG. 23D

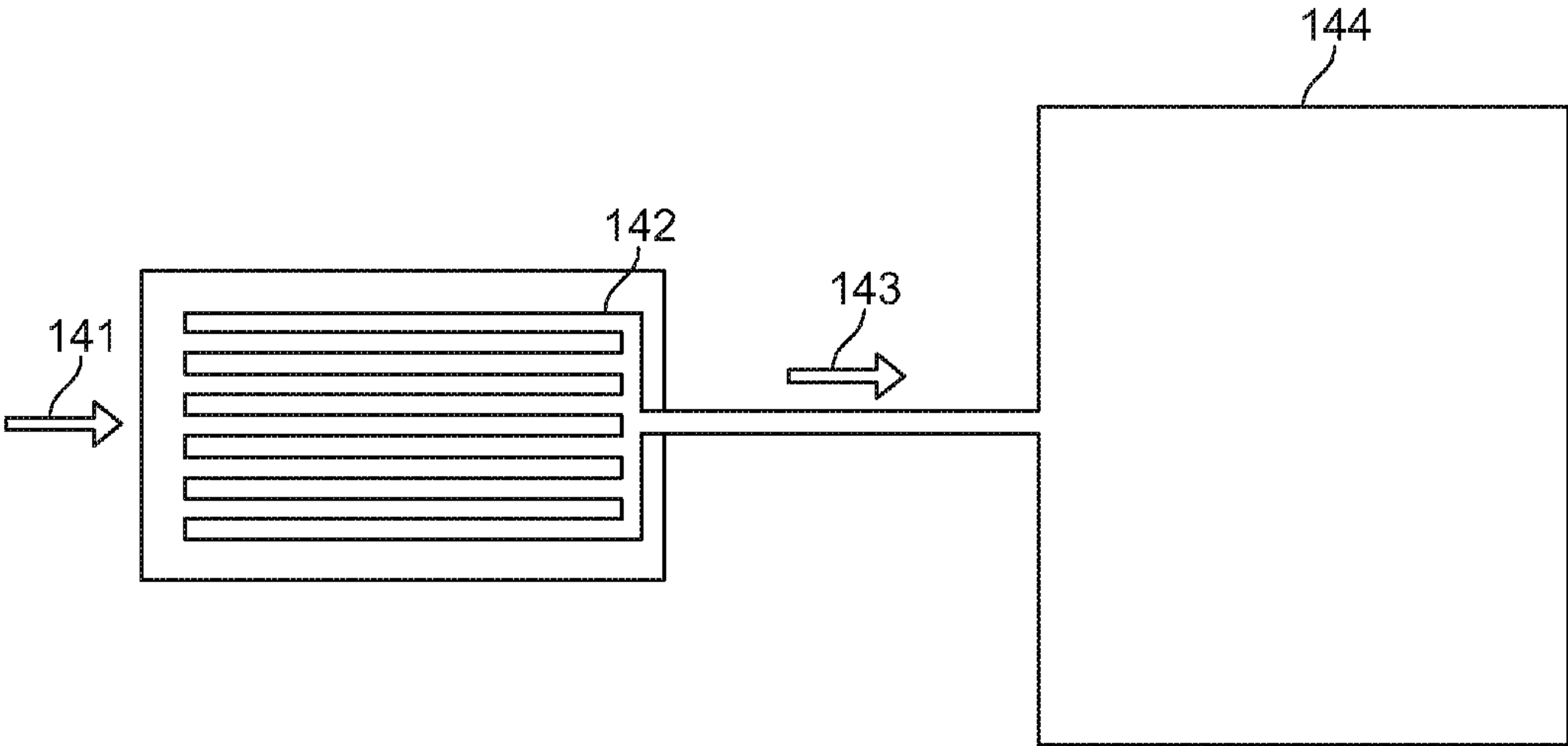


FIG. 24A

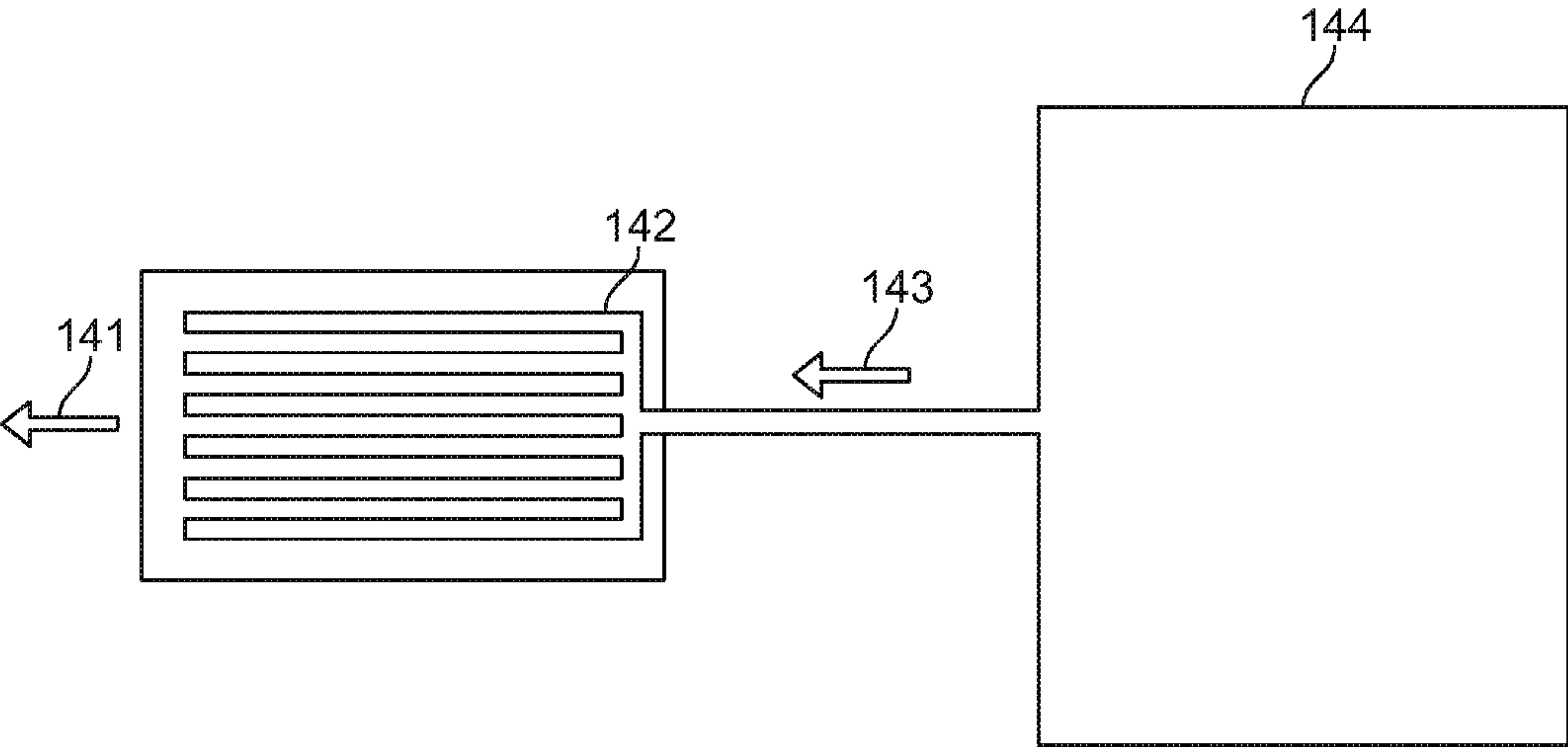


FIG. 24B

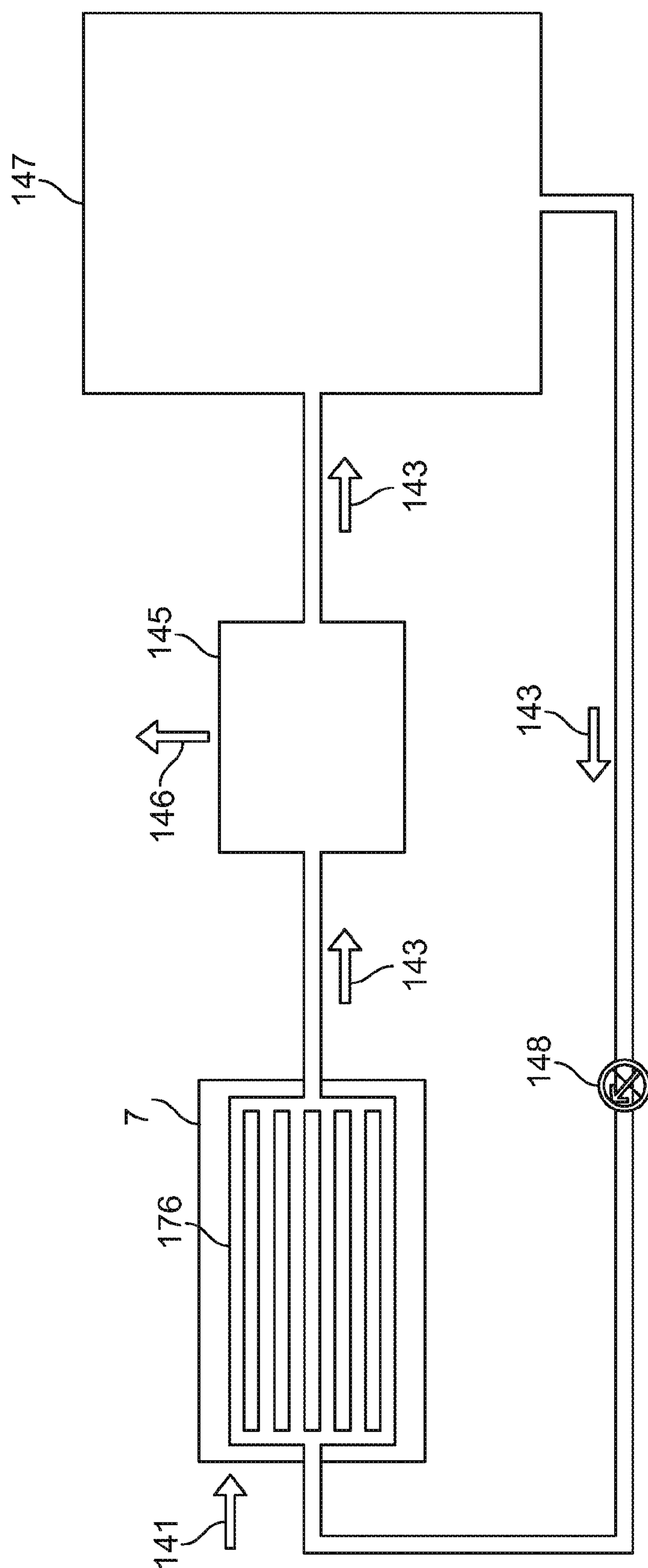


FIG. 25A

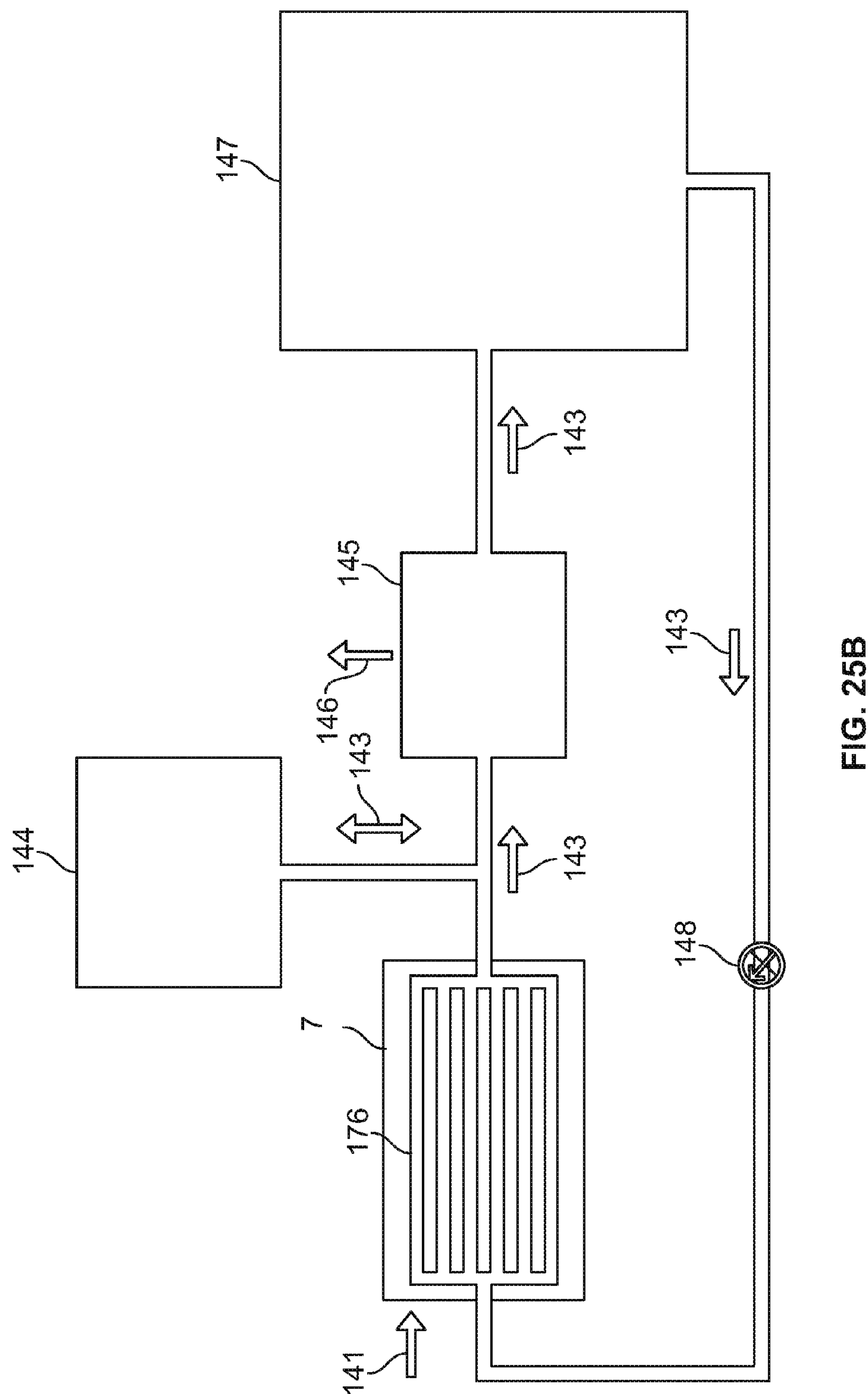
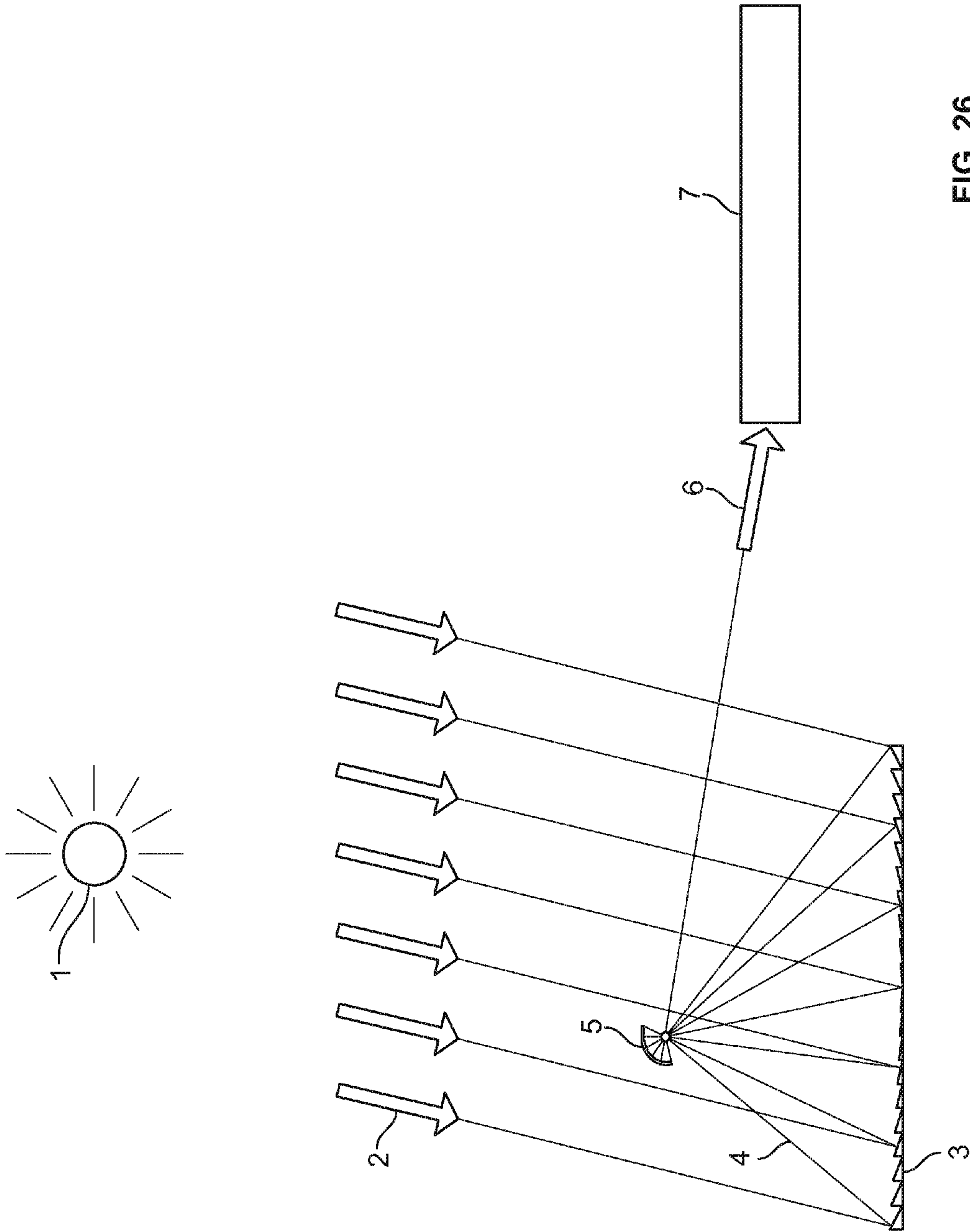


FIG. 25B



SOLAR CONCENTRATOR SYSTEM FOR SOLAR ENERGY PLANTS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of provisional application Ser. No. 61/245,250, filed Sep. 23, 2009 which is herein incorporated by reference.

TECHNICAL FIELD

[0002] This disclosure relates to a solar concentrator system for solar energy plants.

BACKGROUND

[0003] Solar energy is emerging as one of the most promising sustainable energy sources. A solar energy plant takes solar energy and converts it to useful energy and/or products. A solar electrical plant takes solar energy and converts it to electrical energy. Solar energy has impressive potential: the entire world could theoretically be supplied with its current needs for electricity from solar power stations covering only approximately 1% of the earth.

[0004] As illustrated in FIG. 1A, a solar concentrator system collects incoming direct solar irradiation **2** from a collection field and concentrates it to a smaller solar receiver region. The purpose of a solar concentrator system is to concentrate solar irradiance for later conversion into other forms of usable energy, such as solar thermal to electrical energy. A concentrating solar energy plant is a solar plant composed of two major parts: a solar concentrator system **8**, and a power-block **140**, which converts secondary concentrated solar radiation **6** to energy and/or useful products.

[0005] Concentrated solar thermal-electrical plants are solar power plants that make use of solar irradiation (primarily in the infrared (IR) range) to generate electricity. Each square meter of land in the United States Southwest receives approximately 5 to 8 kilowatt hours (kWh) of solar irradiation each solar day, depending on season and weather conditions. A report entitled Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts by Sargent and Lundy LLC Consulting Group, National Renewable Energy Laboratory, Chicago, Ill., (October 2003), herein referred to as "the Sargent and Lundy report," made a cost analysis that implies the currently operating large scale solar concentrating and collecting systems produce electricity (per kWh) at a cost (including finance costs for construction) of roughly between two and five times of the current commercial market price of electricity (per kWh). The detailed amortized cost analysis of these current solar concentrator systems, according to the report, implies a very long payback period, approaching a given system's expected functional lifetime.

[0006] Solar photovoltaic (PV) plants make use of photovoltaic (PV) cells to generate electricity. The most efficient PV plants make use of concentrated solar radiation primarily in the ultraviolet (UV) and visual (VIS) ranges. Compared to the key components of solar thermal systems, PV cells generally degrade more rapidly, making them at this time a less preferable choice for large-scale electrical generation than solar thermal-electrical plants. However, solar PV plants have

distinct advantages, such as their capability to provide electrical power in remote areas, and their potential portability.

Solar Concentrator Systems

[0007] Solar concentrator systems typically consist of various key optical components: a primary concentrator, possibly a secondary concentrator, a solar receiver containing some form of solar absorber and/or an energy storage system.

[0008] Known large-scale solar concentrator systems can generally be partitioned into four types of categories based on the shape or configuration of their primary concentrating surfaces. These are power tower systems, trough systems, compact linear Fresnel reflector systems, and dish systems. Power tower collectors are comprised of an array of heliostats, which individually track to concentrate solar radiation to a central, and usually raised receiver. The primary concentrators of trough systems have curved trough shape or a faceted approximation, which concentrate solar radiation to their focal line. The primary concentrators of compact linear Fresnel reflector systems are flat reflective strips, which are rotated to concentrate solar radiation to their focal line. The primary concentrators of dish systems have curved dish shape or a faceted approximation, which concentrate solar radiation to a single focal point. There are numerous currently operational examples of power tower, trough and dish systems.

[0009] Though the classification above is useful for describing the geometry of concentrating systems, when determining the cost efficiency of the systems, it is preferable to categorize solar systems based on whether key parts (e.g., primary concentrators, secondary concentrators, and solar collectors) are immobile or mobile. As stated above, one limiting factor of solar system design is the high initial cost of construction. Much of this construction cost comes from either or both the mechanisms for tracking and control of mobile concentrators and the structural elements necessary for supporting primary collectors in configurations that are exposed to the wind and other weather elements.

[0010] In any solar concentrator system, the primary concentrators, which are the component that receives direct solar radiation, typically have the largest surface area of any component, and thus their design is a large component in terms of costs of the overall system. Most primary concentrators are not horizontal, and are highly exposed to wind forces, often requiring costly structural support structures. Furthermore, most large-scale solar concentrators contain primary concentrators that are tracking, that is, they move to follow the daily movement of sun. In trough concentrator systems, this may manifest in one dimensionally tracking troughs, while in power tower systems, it may involve two dimensionally tracking heliostats. In both cases, these tracking primary concentrators generally make up a large portion of the total cost of the system due to their tracking mechanisms and the structural support structures needed to help them withstand wind and other weather conditions. The Sargent and Lundy report made a component cost breakdown for a 2004 trough system and estimated that thirty-five percent of the cost was due to the metal support structure and drive, which together comprise the tracking and control system for the primary concentrators. The primary concentrators of compact linear Fresnel reflector systems can be placed on the ground at near horizontal position, but the primary concentrators are required to track, increasing their complexity and construction costs.

[0011] There are also prior solar concentrator systems that include secondary reflectors, which may or may not track. For

example, in some systems the primary and secondary concentrators are fixed in relation to each other but move as a unit to track, which still necessitates moving parts and a support structure.

[0012] Solar receivers have an important component, absorbers, whose function is to receive the concentrated solar energy for the purpose of storage or energy conversion. Generally absorbers have low cost compared to the cost of the solar concentrator system. The locations of the absorbers may vary in solar collectors; a concentrating solar system is defined to have localized absorbers if a distinct absorber is required for each primary concentrator element, whereas a concentrating solar system has centralized absorbers if multiple concentrators direct solar energy to a small number of absorbers. The use of localized absorbers often results in a more complex and costly heat transport and conversion system. Furthermore, the efficiency of heat energy conversion is increased with a higher temperature differential. Since localized absorbers generally have a lesser concentration of solar radiation and their temperature is lower, making these systems less efficient, and therefore less preferable. The lower concentration of solar radiation, and the lower temperatures that follow, also increase the emittance of localized absorbers; test results show that absorbers which used black chrome and Luz Cermet receiver tubes, for example, have a thermal emittance (the quantity emitted per unit area, which corresponds to thermal loss) of only nine percent at temperatures above 400 degrees Fahrenheit (The Sargent and Lundy report, §4.2.2). Presently, the majority of concentrators on the market have localized absorbers. Such localized absorber systems, in some examples, include large scale trough concentrators, large dish concentrators, and almost all smaller scale concentrators. Solar power towers are one of the few centralized absorber systems.

[0013] In addition to absorbers, solar receivers generally also include a means for storage of the energy collected by the absorbers. The energy storage period may be temporary or may be for a longer period beyond the period of the solar day. In the case of solar-thermal solar concentrator systems, energy storage can be achieved by a material or medium for storage of the heat energy, which may be temporary or may be for a longer period.

[0014] Since solar energy can only be collected for a portion of the solar day (typically approximately 8 hours a day), it follows that without a means for energy storage, the generator would only be able to produce electricity for that portion of the solar day. During this window of time, the generator would have to convert all of the collected solar radiation. In typical practice, by using an energy storage medium, the generator can potentially run up to three times longer, providing approximately one third the power over a twenty-four hour period. In solar energy systems with energy storage, the receiver can serve to absorb the energy from focused solar radiation and store in thermal energy storage substances, phase change materials, or chemical energy storage substances.

[0015] Bulk thermal storage mediums store energy by simply heating the medium. Thermal energy storage substances include, in some examples, liquid sulfur, molten salt, fluoride-salt, and various mineral oils.

[0016] Phase-change materials make use of a change in state (e.g., from solid to liquid, or from liquid to gas) for energy storage. For example, various materials include water, which can be used to store and release heat by evaporating

into steam and condensing back to liquid state, or alternatively various salts can be used to store and release heat by melting and solidifying, respectively.

[0017] Chemical storage mediums make use of chemical reactions to store and release heat. Chemical storage mediums, in some examples, include metal hydrides, such as magnesium hydride, which store energy by dissociation to the base metal and hydrogen gas.

[0018] In summary, energy storage systems add to the initial cost of a solar power plant, but provide for extended daily periods of electrical output beyond the period of solar exposure, allowing electrical generators to be used extended periods of up to a full twenty-four hours rather than the approximately (depending on latitude and season) eight hours of usable direct sunlight, with only a very small decrease the efficiency. This would at first appear to significantly lower the amortization costs for the electrical generators by a factor of three per kWh (as they are used for three times as long at a third of the power). However, as detailed in the Sargent and Lundy report §4.3, the cost for energy storage was approximately 150% of the cost for the electrical generators, which implies a total of approximately 250% increased cost of constructing the power (storage and conversion) block, so the effective decrease in power-block cost by the use of energy storage is approximately $2.5/3$ or about 83%.

Power Block of Solar Electrical Plants

[0019] The portion of a solar energy system that transforms solar energy to other useful products or energy, such as electricity, is termed the power-block. The power-block, as referred to herein, includes generators that transform solar energy to electricity as well as possibly energy storage devices.

[0020] The efficiency (the ratio of the energy output to the energy input) and cost of the means for energy conversion from concentrated solar energy into electricity is critical. The maximum Carnot efficiency of a reversible system for conversion of heat energy to mechanical power, for example, is lower bounded by $1-r$, where r is the ratio of the cooled (ambient) temperature to the heated temperature (where both temperatures given are in degrees Kelvin). In practice, the efficiency of typical nonreversible systems for conversion of heat energy to electrical power has been empirically found to limit (for large generator systems) to approximately $1-r^{1/2}$. In either formula, the key quantity r is minimized when the heat differential between the cooled (ambient) temperature and the heated temperature is maximized.

[0021] Most concentrated solar thermal-electrical plants use turbines as means for converting thermal energy into electricity. Turbines can have efficiencies of up to 33% (depending on the size of the generator), and this can rise to as high as 42% efficiency if a reheat turbine cycle is used. The estimated yearly electrical income per kWh for concentrated solar thermal-electrical plants is less than the initial cost of purchase of steam turbines per kWh. However, this cost encompasses only the steam turbine, not the entire heat conversion system. This entire power-block is comprised of the steam turbine, cooling towers and piping systems. In prior art trough solar plants; the power-block can make up approximately 14% of the total cost (The Sargent and Lundy Report, §4.3).

[0022] Another variety of solar system includes cogeneration systems that, in addition to generating electrical energy from heat, also make further productive use of the waste heat,

for example for steam or hot water heating of buildings. Such cogeneration systems can thus make productive use of upwards of between 85% and 90% of the input heat energy.

SUMMARY

[0023] Certain embodiments make use of an array of passive primary concentrators positioned on the ground, that provide primary concentrated solar radiation from below to an array of tracking secondary concentrators, which then further concentrate the solar radiation to one or more centralized solar energy receivers.

[0024] The solar concentrator system may include apparatus for collection of solar radiation, concentration, and the absorbance of the concentrated solar energy. Some embodiments of the solar concentrator system include a large field of inexpensive, passive horizontal primary concentrators, overhead tracking secondary concentrators, and one or more receivers, which convert solar radiation into usable products or energy, such as electricity. A power-block may store and convert the concentrated solar energy to useful products.

[0025] FIG. 1B summarizes an embodiment of the flow of energy through the solar concentrator system, where **1** is the Sun, **2** is direct solar radiation, **3** is a (saw-tooth contoured) primary concentrator, **4** is the primary concentrated solar radiation directed from a primary concentrator, **5** is a secondary concentrator, **6** is further concentrated solar radiation directed from secondary concentrator, **7** is a receiver of the concentrated solar energy.

[0026] A field used for collection of solar radiation from the sun is termed the primary concentrating field; in some embodiments, the primary concentrating field is fixed on the ground (immobile) and may be constructed out of an inexpensive material, such as concrete. The field may be subdivided into units, called primary concentrators. In certain embodiments, the primary concentrators are linear optical concentrators. In other words, the primary concentrators focus light to a region of focus, generally of uniform height above their surface, which will be termed the primary concentrator's focal line. In certain embodiments, due to in part to off-axis aberrations, optical surface defects and other effects, this focal line may broaden to a narrow horizontal strip. Each primary concentrator may have an optical surface with a saw-tooth cross section which provides an initial concentration of direct solar radiation. In other embodiments, the optical surface of the primary concentrators has a parabolic cross section. The optical surface may be purely reflective. In some embodiments, the optical surface may include both refractive and reflective elements. In certain embodiments, the optical surface of the primary concentrators includes a series of elongated convex cross section. In some embodiments, the optical surface includes a plurality of reflective optical elements.

[0027] In certain embodiments, the primary concentrators are stationary and, as the sun moves throughout the day, the primary concentrators' focal line moves across the focal plane in a west to east direction. In other embodiments, the focal line of the primary concentrators moves across the focal plane in an east to west direction. The optical surfaces of the primary and secondary concentrators may provide high optical efficiency, in particular high spectral reflectance. In some embodiments, the optical surfaces of the primary concentrators are mirror films that are very durable, and inexpensive to replace. In some embodiments, the optical surfaces of the secondary concentrators are extremely durable metallic surfaces with protective coating, insuring a long lifetime.

[0028] Each secondary concentrator may have one or two optical surfaces, each of which may be a linear optical concentrator. In some embodiments, the optical surfaces of the secondary concentrators are purely reflective. In other embodiments, the optical surfaces of the secondary concentrators include both refractive and reflective elements. In an embodiment, the optical surfaces are reflective and concave in cross section. In alternative embodiments, the optical surfaces of the secondary concentrators may include refractive as well as reflective elements. In some embodiments, the optical surfaces have a saw-tooth cross section. In other embodiments, the optical surfaces are parabolic in cross section.

[0029] The array of secondary concentrators may further concentrate the solar radiation and direct it to one or more receivers. In certain embodiments, the array of secondary concentrators is positioned to direct concentrated solar radiation to the receiver or receivers without obstructing one another. Each secondary concentrator may be suspended above the solar collecting field so that at any given time, the focal line (this is the hypothetical line at which parallel rays emitted from the receiver would be focused by the active optical surface of the secondary concentrator) of an optical surface of the secondary concentrator coincides with the focal line of the primary concentrator associated with the secondary concentrator. In some embodiments, to maintain the active optical surface of the secondary concentrator coincident with the focal line of the primary concentrator, the secondary concentrator can be moved throughout the solar day. In other words, adjustments of the secondary concentrator can be used to track the focal line of initially concentrated solar radiation reflected from the primary concentrator. In other embodiments, simultaneous tracking movements may be made to insure the fully concentrated solar radiation departing from the secondary concentrator is always directed toward one of the receivers. The secondary concentrators may track on an east-west axis parallel to the plane of the ground. In some embodiments, the secondary concentrators rotate vertically during tracking. In other embodiments, the secondary concentrators rotate during east-west tracking of the focal line. In some embodiments, the secondary concentrators suspended overhead on cables that allow movement of the secondary concentrators while tracking the focal line of the primary concentrator.

[0030] In certain embodiments, the receivers are located centrally in the primary concentrating field. In other embodiments, the receivers are located outside the field. In alternative embodiments, the receivers are able to adjust their locations depending on the time of year.

[0031] The solar concentrator system may be used in conjunction with a heat storing apparatus. In some embodiments, the heat storing apparatus includes a bulk heat storage medium (e.g., water, oils, sulfur, or concrete). In certain embodiments, the heat storing apparatus is a phase change medium (e.g., via the melting of salts or water/steam conversion). In alternative embodiments, the heat storing apparatus is a chemical heat storage system (e.g., metallic hydride reactions liberating hydrogen).

[0032] In selected applications, the solar concentrator system may be used in conjunction with an apparatus for converting the solar radiation collected from the field into usable energy. In some embodiments, high concentration solar cells are used to convert solar radiation into energy. In other embodiments, a smelting or hydrogen production apparatus

are used to convert the solar radiation into energy. In alternative embodiments, a steam turbine converts the solar radiation into energy or heat.

[0033] In selected large-scale utility applications, for example using multiple solar concentrator systems combined in a compact scalable fashion, apparatus for storing solar radiation and conversion into usable energy may be shared amongst two or more solar concentrator systems.

[0034] A solar concentrator system including immobile primary concentrators, tracking secondary concentrators and centralized receivers to which solar radiation is directed may use an array of passive primary concentrators positioned on the ground, such that primary concentrated solar radiation can be provided from below to the array of tracking secondary concentrators. The array of tracking secondary concentrators may then further concentrate the solar radiation to the two centralized receivers. The design of the solar concentrator system may provide a dramatic reduction in costs for construction and maintenance while maintaining a high energy-efficiency, longevity, and broad applicability. In particular, two aspects of the solar concentrator system may provide a dramatic reduction in costs for construction and maintenance. First, a key item of cost advantage can include the use of immobile primary concentrators positioned on the ground, which therefore do not require costly large-scale structural support. Secondly, the use of tracking secondary concentrators suspended overhead on cables can also provide a significant cost-savings for construction. Additionally, the design of these two features may reduce of other recurring costs (such as maintenance). The high energy-efficiency design of the solar concentrator system, in combination with the reduction in costs for construction and maintenance, may imply a short payback period for combination of the initial costs and the recurring costs to be amortized.

[0035] The optical surfaces of the primary and secondary concentrators may provide high optical efficiency, in particular high spectral reflectance. The use of centralized receivers, to which solar radiation is directed, can significantly increase the energy-efficiency of the system, since heat does not need to be transported, and heat storage systems can be easily configured at the centralized receivers.

[0036] A high longevity may be provided by the ground-based positioning of the primary concentrators, allowing limited exposure to weather-related degradation such as wind loads. The low aspect and simplicity of the cable suspension of the secondary concentrators may also provide features that extend the lifetime of the solar concentrator system. The optical surfaces of the primary concentrators, in another example, can be constructed of mirror film that is very durable yet inexpensive to replace. The optical surfaces of the secondary concentrators, in another example can be constructed of extremely durable metallic surfaces with protective coating, insuring a long lifetime.

[0037] To provide the broadest base of application, the solar concentrator system can provides concentrating of a wide spectrum of solar radiation, including both IR (for example for solar-thermal electrical plant applications), as well as UV and VIS (for example for PV electrical power plant applications).

BRIEF DESCRIPTION OF DRAWINGS

[0038] FIG. 1A illustrates a solar energy plant composed of a solar concentrator system and a power-block.

[0039] FIG. 1B summarizes a flow of energy through the solar concentrator system of FIG. 1A.

[0040] FIGS. 2A and 2B show examples of primary concentrators.

[0041] FIG. 3 shows (in 3D) a solar collecting field composed of bidirectional primary concentrators.

[0042] FIGS. 4A and 4B show examples of primary concentrators with a saw-tooth surface patterning.

[0043] FIGS. 5A-5F show examples of the concentration of solar radiation by one or more solar concentrators.

[0044] FIGS. 6A-6C show examples of the concentration of solar radiation by an individual primary concentrator and an associated secondary concentrator into a solar energy receiver.

[0045] FIGS. 7A-7K detail various types of secondary concentrators.

[0046] FIGS. 8A-8C are illustrations of examples of secondary concentrators suspended by cables.

[0047] FIG. 9 is an illustration of an example of a field of bidirectional primary concentrators, with associated doubled secondary concentrators, their support via support cables and poles.

[0048] FIG. 10 illustrates the geometry optionally employed for avoiding optical obstructions between secondary concentrators.

[0049] FIGS. 11A-11D show examples of how a singleton secondary concentrator can be equipped with one or multiple pivots to allow it to be folded into a protective clamshell position.

[0050] FIGS. 12A-12D show examples of how a double secondary concentrator can be equipped with one or multiple pivots to allow it to be folded into a protective clamshell position.

[0051] FIGS. 13A-13B illustrate example positioning of a secondary concentrator so that its receiver-directed focal line coincides with the focal line of the primary concentrator.

[0052] FIG. 13C is an illustration of an example of how the east-west slant of the focal plane of a primary concentrator can conform to the local slant of the support cables above.

[0053] FIGS. 14A-14C show various exemplary positions of the extended focal line of the primary concentrator over the day, along with the corresponding position of the secondary concentrator.

[0054] FIGS. 15A-15D show examples of a daily schedule used for positioning a secondary concentrator.

[0055] FIGS. 16A-16E show tracking apparatus with illustrations at various distinct times throughout the day of the translational tracking of a non-rotating non-elevating doubled secondary concentrator as well as illustrations of the radiation entering the doubled secondary concentrator from the bidirectional primary concentrator.

[0056] FIG. 17A shows determination of the secondary concentrator's vertical angle from the horizontal to the mid-line of the receiver.

[0057] FIGS. 17B-17F shows examples of how daily vertical translations of the secondary concentrator of FIG. 17A can be used to improve the performance of the secondary concentrator.

[0058] FIG. 17G illustrates an example of a vertically tracking, non-rotating double secondary concentrator.

[0059] FIGS. 17H-17K show the apparatus of FIG. 17G with illustrations at various distinct times throughout the day of the translational tracking.

[0060] FIG. 17L shows an illustration of the daily movements illustrated in FIGS. 17H-17K, condensed into one figure.

[0061] FIG. 18A illustrates an example of the definition (in 2D cross section) of the angle of rotation of the secondary concentrator.

[0062] FIGS. 18B-18E show how daily counterclockwise rotations of a secondary concentrator can be used to improve its performance.

[0063] FIG. 18F shows an illustration of the daily counterclockwise rotations illustrated in FIGS. 18B-18E condensed into one figure.

[0064] FIG. 19A illustrates an example of a rotating non-elevating double secondary concentrator.

[0065] FIGS. 19B-19F show the apparatus of FIG. 19A, with illustrations at various distinct times throughout the day of the translational tracking.

[0066] FIG. 20A illustrates an example of a rotating non-elevating singleton secondary concentrator with a cam disk and cam guide.

[0067] FIGS. 20B-20G illustrate the apparatus of FIG. 20A, with position of the engaged single cam and secondary concentrator at various angles of rotation at five exemplary times throughout the day.

[0068] FIG. 21 illustrates an example pair of horizontally separated refractive secondary concentrators, where each concentrator has a saw-tooth contoured operationally-refractive optical surface, and both concentrators are non-rotating and non-elevating and attached to the same two support cables.

[0069] FIG. 22 illustrates an example pair of horizontally separated refractive secondary concentrators, where both are non-rotating and non-elevating and attached to the same two support cables.

[0070] FIG. 23A illustrates an example of how secondary concentrators can swivel slightly away from the north-south axis to compensate for the changing slant of the concentrated solar radiation over the year.

[0071] FIG. 23B illustrates an example of how receivers can move on the north-south axis to slowly track over the year the changing north-south location of the concentrated solar radiation from the secondary concentrators, so as to capture this concentrated solar radiation.

[0072] FIG. 23C illustrates an example of a receiver with a vertically stacked array of horizontal evacuated receiver tubes, arranged in a linear pattern, used as absorbers of the concentrated solar radiation.

[0073] FIG. 23D illustrates an example of a receiver with a collection of horizontal evacuated receiver tubes, arranged in a zig-zag pattern, used as absorbers of the concentrated solar radiation.

[0074] FIGS. 24A and 24B illustrate example apparatus for storage of the concentrated solar energy using a magnesium hydride.

[0075] FIGS. 25A and 25B illustrate an example solar concentrator system including a power block.

[0076] FIG. 26 illustrates an example of the concentrated solar radiation from secondary concentrators directed a receiver, partitioned into two subreceivers.

[0077] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0078] A solar concentrator system includes an apparatus for the collection of solar radiation, concentration, and the absorbance of the concentrated solar energy. As shown in FIG. 1B, an example of a flow of energy through a solar concentrator system includes a solar energy source (e.g., the Sun) 1 providing direct solar irradiation 2, a (saw-tooth contoured) primary concentrator 3, primary concentrated solar radiation 4 directed from a primary concentrator 3, a secondary concentrator 5, secondary concentrated solar radiation 6 directed from the secondary concentrator 5, and a receiver 7 of the secondary concentrated solar radiation 6.

[0079] A solar collecting field configured to receive direct solar radiation can be designed to minimize construction and maintenance costs while providing highly efficient concentration of solar energy. In certain embodiments, the collecting field is positioned on a flat, horizontal plane and is rectangular in shape. The collecting field is oriented so that two opposing sides, where solar receivers are located, are positioned for example on the east and west sides of the field. The solar radiation in the initial part of the solar day will be concentrated to the east solar receivers and in the later part of the solar day solar radiation will be concentrated to the west solar receivers. The solar receivers are rectangular in shape with a midline at a fixed height H. In some embodiments, the two opposing sides are positioned generally on the east and west sides of the field. In other embodiments, the two opposing sides are positioned generally on the north and south sides of the field. In certain embodiments, there is exactly one solar receiver on each of the solar receiver sides. In other embodiments, there are between approximately two and approximately nine solar receivers on each of the solar receiver sides, preferably between three and seven, more preferably five.

[0080] In certain embodiments, the solar collecting field is horizontal and composed of an array of primary concentrators. Each primary concentrator is rectangular in shape. Each primary concentrator has as its upper surface an optical surface that provides an initial concentration of direct solar radiation. The surface of each primary concentrator has a saw-tooth contour, with troughs that run in the in a north-south direction. In other embodiments, the troughs run in an east-west direction. In certain embodiments, the optical surface of the primary concentrators includes a series of elongated convex forms. The initial concentration of solar radiation provided by the primary concentrator, and directed above it, will be termed the primary concentrated solar radiation. The optical surface of each primary concentrator, in some implementations, is purely reflective. In other embodiments, the primary concentrator is both reflective and refractive. In certain embodiments, the primary concentrators are stationary. When the primary concentrators are stationary the primary concentrated solar radiation moves in a west to east direction above the primary concentrators when the sun moves across the sky. In certain embodiments, the primary concentrated solar radiation moves in an east to west direction above the primary concentrators.

Primary Concentrator Design

[0081] In some implementations, the primary concentrators have a saw-tooth contour on their optical surfaces con-

sisting of a series of elongated strip-shaped facets which are concave and run linearly in a north-south direction. In some embodiments, the optical surfaces run linearly in an east-west direction. In alternative embodiments, the series of elongated strip-shaped facets are flat. The primary concentrators, in some implementations, are bidirectional. In other embodiments, the primary concentrators are unidirectional. As illustrated in FIG. 2A, the strips of a unidirectional primary concentrator **3a** are either all oriented east or all oriented west. The optical surface of a bidirectional primary concentrator **3b**, as shown in FIG. 2B, has a sequence of strips on its optical surface running from west to east. The strips, for example, begin at the west end oriented east, and then are followed (progressing to the east) by a further sequence of strips that are oriented west. The top surface of the bidirectional primary concentrator **3b** has a first portion **150a** and a second portion **150b**, the first portion **150a** including the generally west half of the bidirectional primary concentrator **3b**, and the second portion **150b** including the generally east half of the bidirectional primary concentrator **3b**. The first and second portions **150** slope generally downward toward the center of the bidirectional primary concentrator **3b**. In other embodiments, the first and the second portions **150** slope generally downward toward a first and a second edge of the bidirectional primary concentrator **3b**, where the first and second edges are located on opposite sides of the bidirectional primary concentrator **3b**.

[0082] In alternative embodiments, the optical surface of each primary concentrator is parabolic in cross section.

[0083] In some embodiments, the primary concentrators are slightly slanted so the troughs of the primary concentrators can serve as a runoff system. For example, runoff from the troughs of the primary concentrators can be fed into an additional water drainage system in the case of heavy rains.

[0084] FIG. 3 shows an example solar collection field **9** composed of an array of bidirectional primary concentrators **3b**. The solar collection field **9** includes multiple bidirectional primary concentrators **3b** in an array that is approximately horizontal. The bidirectional primary concentrators **3b** located in the same column all have the same layout, such that the first and second portions of each bidirectional primary concentrator **3b** slope generally downward toward the center of the bidirectional primary concentrator **3b** along a longitudinal axis that passes through all of the bidirectional primary concentrators **3b** in the column. The longitudinal axis, in some implementations, runs along a generally north-south axis. In other embodiments, the longitudinal axis runs along a generally east-west axis.

[0085] In certain embodiments, the solar collection field **9** contains a first half and a second half. Each half includes multiple bidirectional primary concentrators **3b** generally sloped in the same direction. For example, the first half can be positioned on the west side of the solar collection field **9** and have a downward slope toward the western longitudinal edge of the solar collection field **9** and the second half can be positioned on the east side of the solar collection field **9** and have a downward slope toward the eastern longitudinal edge of the solar collection field **9**. In other embodiments, the first and the second halves slope generally downward toward the center of the solar collection field **9**. In some embodiments, the first half is positioned on the north side of the solar collection field **9** and the second half is positioned on the south side of the solar collection field **9**.

[0086] Since the function of each primary concentrator, such as unidirectional primary concentrator **3a** and bidirectional primary concentrator **3b**, is to collect and initially concentrate the direct solar radiation from the sun, the primary concentrators comprise the vast majority of the bulk of materials of the solar concentrator system. In some embodiments, depending on the ground contour of the site, there may be the need for minimal gravel grading of the ground to insure it is sufficiently flat. Each primary concentrator can be constructed from one or more low cost structural blocks. The structural blocks can be composed of concrete. In another example, the structural blocks can be made from plastic. In some embodiments, the blocks are made from a metallic material. In other embodiments, the blocks are made from wood or a wood compound. In certain embodiments, the material used to create the blocks is optically clear. In still other embodiments, the structural blocks are made from a plant product other than wood. These blocks can be preformed offsite or cast on site using molds. Each mold, for example, creates one block. In other embodiments, a single mold creates multiple blocks at a time. In certain embodiments, the blocks are formed offsite at a manufacturing plant and transported to the solar collection field. In certain embodiments, a sheet of wire mesh may be cast inside of these blocks to add structural support. On the upper surface of each primary concentrator, for example, can be one or more layers of a material such as plastic, which aids in defining the shape of the optical surface, smoothes the upper surface, and also provides sheathing protection from weathering. A highly reflective metallic film, in some implementations, is adhered to the uppermost surface of the primary concentrator. The spectral reflectance of an optical surface is the percent of incoming radiation that is directly reflected, and neither absorbed nor diffused in some other direction. Mirror films designed for solar concentration applications generally are designed to be inexpensive, durable, and have a high reflectance; for example ReflecTech, Inc. of Picayune, Miss. produces a mirror film which has 94% spectral reflectance, and has been demonstrated to be durable without significant damage in the outside environment in Colorado for over ten years.

[0087] FIG. 4A shows an example composition of one of the primary concentrators constructed from a structural material **10** such as concrete or plastic, saw-tooth surface patterning with troughs **11**, covered with sheathing **12**, such as ABS, attached to the structural material for the primary concentrator, and an external reflective film **14**. An alternative embodiment of portable, low cost primary concentrators, as illustrated in FIG. 4B includes optical surfaces of each primary concentrator with both refractive and reflective elements. The optical element of each primary concentrator, for example, includes a refractive optical sheet **15** with saw-tooth surface patterning and with a reflective backing **16**.

[0088] The optical surface of each primary concentrator can be designed to form a linear concentrator so that for any given position of the sun, the concentrated solar radiation is focused (roughly) into a single line segment, for example the focal line of the secondary concentrators. In certain embodiments, the optics of each primary concentrator are designed so that this focal line is at all times horizontal, is oriented north-south, and moves in a plane (the primary concentrator's focal plane) predictively through the course of the day. In other embodiments, the focal line has an east-west orientation.

[0089] Each north-south row of primary concentrators, in some implementations, has co-planar focal planes. Each east-west row of primary concentrators, for example, can be configured to have no slant in the north-south direction (since the focal lines are horizontal and run north-south).

[0090] An extended focal line, for example, is the line extending the focal line segment for a single primary concentrator over the collection field to the north and south. Over the day, the extended focal line of the primary concentrators drifts from west to east. FIGS. 5A (in 2D cross section) and 5B (in 3D) illustrate the concentration of primary concentrated solar radiation 4 by the bidirectional primary concentrator 3b into its focal line 20, with extended focal line 21.

[0091] If, for example, the focal planes of all the primary concentrators were co-planar and horizontal, at a fixed height above the plane, then the focal line of all primary concentrators would simply remain at this fixed distance above the primary concentrator at all times of the day. In an alternative embodiment, each east-west row of primary concentrators has a focal plane with distinct slants slightly away from horizontal. A reason for this is that each east-west row of secondary concentrators may be hung via east-west cables that change in height and slant in the east-west direction, requiring the design of distinct optical surfaces for each primary concentrator along a east-west row, so their focal plane's east-west angle of slant is approximately the same as the average (e.g., averaged over the east-west extent of the primary concentrator) local angle of slant of the support cables above them. FIGS. 5C (in 2D cross section) and 5D (in 3D) provide a sequence of example focal planes 22 (which change their east-west slant, but have no slant in the north-west direction) of a sequence of bidirectional primary concentrators 3b in the east-west direction.

[0092] FIG. 5E illustrates (in 2D cross section) the positioning of a secondary concentrator 5 so that its receiver-directed focal line 60 coincides with the focal line 20 of the bidirectional primary concentrator 3b.

[0093] FIG. 5F illustrates (in 3D) the positioning of the secondary concentrator 5 so that its receiver-directed focal line 42 coincides with the focal line 20 of the primary concentrator.

[0094] The primary concentrator can be designed to have a high optical efficiency and low cost by use of reflective film and concrete base structure. The primary concentrator's solar efficiency (which here is determined by the spectral reflectance of the primary concentrator), for example, ranges from approximately 85-99%, preferably 90-97%, more preferably 92-96% for the surfaces exposed to direct solar radiation. In some embodiments, the spectral reflectance of the primary concentrator is approximately 94%. The most exposed portion of the primary concentrator is the mirror film, which has a demonstrated expected outdoor life of over ten years; therefore, the primary concentrator can be expected to last for at least this period with out serious repairs, and these repairs would be mostly limited to simply the replacement or repair the reflective film.

[0095] A secondary concentrator can be associated with each primary concentrator. Each secondary concentrator, in some implementations, can be oriented north-south parallel with the axis of the troughs of its corresponding primary concentrator. In some embodiments, the focal lines of the primary concentrators move in an east to west direction. As the sun moves during the day, the current position of the focal line of the solar radiation concentrated by each primary con-

centrator translates in a west to east direction. The function of each secondary concentrator is to direct the solar radiation concentrated by the primary concentrator to a receiver. FIGS. 6A through 6C illustrate examples of the optical path of the direct solar irradiation 2 from the sun 1, and how the bidirectional primary concentrator 3b and the secondary concentrator 5 concentrate and redirect the direct solar irradiation 2 to the receiver 7. FIG. 6A shows one bidirectional primary concentrator 3b in association with one secondary concentrator 5. The sun 1 directs solar irradiation 2 towards the bidirectional primary concentrator 3b where primary concentrated solar radiation 4 is reflected towards the secondary concentrator 5. The secondary concentrator 5 directs the primary concentrated solar radiation 4, as secondary concentrated solar radiation 6, to the receiver 7. FIG. 6B illustrates a series of bidirectional primary concentrators 3b each directing primary concentrated solar radiation 4 towards a respective associated secondary concentrator 5. The secondary concentrators 5, in turn, direct secondary concentrated solar radiation 6 to the single receiver 7.

[0096] In an alternative configuration, as shown in FIG. 6C, the receiver 7 receives direct secondary concentrated solar radiation 6 from above. The absorbing area of the receiver 7, as illustrated in this example, can be positioned at a height above the ground lower than the height of the secondary concentrators 5, so that the secondary concentrated solar radiation 6 directed to the receiver 7 comes from an angle above the receiver 7. To insure the secondary concentrated solar radiation 6 from each secondary concentrator 5 is directed downward to the receiver 7 without obstruction from other secondary concentrators 5, the receiver 7 can be positioned sufficiently high, and the consecutive secondary concentrators 5 can be positioned sufficiently high and separated in the east-west direction.

[0097] In one embodiment, the optical surfaces of the secondary concentrators are polished aluminum, with a multi-layer dielectric film overcoat multilayer dielectric film overcoat (the dielectric materials may include silicon monoxide or magnesium fluoride) for protection of the optical surfaces.

[0098] In certain embodiments, the secondary concentrator has two optical surfaces, each of which behave as linear optical concentrators and which have a reflecting element. In some embodiments, each secondary concentrator has one optical surface. In alternative embodiments, the optical surfaces have reflecting and refracting elements. In some embodiments, these optical surfaces are purely reflective and concave in cross section. In other embodiments, the optical surface is parabolic in cross section.

[0099] A secondary concentrator with one optical surface can be referred to as a singleton secondary concentrator; where as a secondary concentrator with two optical surfaces (one will face east, the other west) can be referred to as a double secondary concentrator.

[0100] An optical surface of a secondary concentrator can be described as operationally-reflective if it directs primary solar radiation (incoming from the primary concentrator) back in the same general east or west direction from which it came; that is if the optical surface faces generally east, the operationally-reflective secondary concentrator directs radiation from the east back to the east, and if the optical surface faces generally west, the operationally-reflective secondary concentrator directs radiation from the west back to the west. Otherwise, the optical surface can be described as operationally-refractive where, when the optical surface is facing gen-

erally east, the operationally-refractive secondary concentrator directs radiation from the east to the west, and when the optical surface is facing generally west, the operationally-refractive secondary concentrator directs radiation from the west to the east. Note that this terminology only relates to the effect of the optical elements; the actual optical elements in each case may combine reflective and refractive parts.

[0101] In some embodiments, the secondary concentrators have an apparatus for providing vertical elevation (e.g., an elevating secondary concentrator). In certain embodiments, the secondary concentrators have an apparatus for rotation (e.g., a rotating secondary concentrator).

[0102] As mentioned above, each secondary concentrator can be associated with one of the primary concentrators and suspended above it. In certain embodiments, the suspension is implemented using a tensile structure supported by a support structure. A tensile structure, for example, includes elements carrying tension without substantial compression or flexibility. In one example, a system of cables can be used as the tensile structure with support poles as the support structure. In some implementations, the support structure includes a combination of one or more compressive, flexible, or tensile substructures. In some embodiments, the system of cables and support poles includes a tracking apparatus (which will be addressed later). In other embodiments, the secondary concentrators are suspended from a tensile structure. In one example, there are two support cables associated with each east-west row of primary concentrators. These support cables can run parallel to the east-west axis as well as perpendicular to the troughs in the primary concentrators. The support poles, in this case, can be implemented as vertical structural elements whose purpose is to suspend the support cables. The support poles can be positioned in rows along the east and west edges of the solar collecting field. Each support pole can be associated with one or more east-west rows of primary concentrators and can support the support cables associated with these primary concentrators. The apparatus for fixing the support poles into the ground, in some implementations, may include further side cables to provide support. The secondary concentrators can be suspended from these support cables by devices such as rollers that allow the secondary concentrators to move freely along the east-west axis. In other embodiments, there are between two and six support cables for each row of primary concentrators, preferably between two and four.

Secondary Concentrator Design

[0103] FIG. 7A illustrates an example of a non-elevating, non-rotating, double operationally-reflective secondary concentrator **154**, herein referred to as a Type 1 secondary concentrator, suspended by support cables **30**. The Type 1 secondary concentrator **154** can be attached on each side to the support cables **30** in a way that allows for neither rotation nor elevation. In some implementations, the suspension apparatus can also include apparatus for translational tracking in the direction orthogonal (e.g., west to east) to the longitudinal axis (e.g., north-south) of the secondary concentrator **154**. There are four further types of secondary concentrators in alternative embodiments discussed below.

[0104] The Type 1 secondary concentrator **154** can include two concave trough shaped reflective optical surfaces **38** and **39**. In other embodiments, the optical surfaces **38** and **39** of the type 1 secondary concentrator **154** have flat faces. The type 1 secondary concentrator **154**, for example, includes the

eastward-facing optical surface **38** and the westward-facing optical surface **39**. The support system for the Type 1 secondary concentrator **154**, in the illustrated embodiment, includes an immobile support cable **30**, a trolley attachment **31** to the support cable **30**, a plate **32** (e.g., a disk) directly attached to the end of the Type 1 secondary concentrator **154**, and a translational tracking cable **33** used to enable the west to east translational tracking direction of the Type 1 secondary concentrator **154** during the day. An assembly **35** discourages the rotation and vertical elevation of the plate **32** attached to both the support cable **30** (e.g., through the trolley attachment **31**) and the Type 1 secondary concentrator **154**.

[0105] As shown in FIGS. 7B through 7D, three alternative embodiments of secondary concentrators are shown: an elevating, non-rotating double operationally-reflective secondary concentrator, herein referred to as a Type 2 secondary concentrator, a rotating, non-elevating, double operationally-reflective secondary concentrator herein referred to as a Type 3 secondary concentrator, and a rotating, non-elevating, singleton operationally-reflective secondary concentrator herein referred to as a Type 4 secondary concentrator.

[0106] FIG. 7B provides an illustration of an example of a Type 2 secondary concentrator **156** with two concave trough shaped reflective optical surfaces **38** and **39** and its support system (e.g., support cables **30**, trolley attachment **31**, plate **32**, and translational tracking cable **33** similar to those described in relation to FIG. 7A). Assembly **36** is attached to the trolley attachment **31**. Assembly **36**, for example, has a slot for the vertical movement of a pin that protrudes from the plate **32**. Hence, the assembly **36** can allow for free vertical elevation (but no rotation) of the Type 2 secondary concentrator **156**.

[0107] FIG. 7C provides an illustration of an example of a Type 3 secondary concentrator **158** with two concave trough shaped reflective optical surfaces **38** and **39** and its support system (e.g., support cables **30**, trolley attachment **31**, plate **32**, and translational tracking cable **33** similar to those described in relation to FIG. 7A). An assembly **37**, attached to the trolley attachment **31**, has a freely rotatable knob that can allow for rotation (but no vertical elevation) of the Type 3 secondary concentrator **158**.

[0108] FIG. 7D provides an illustration of an example of a Type 4 secondary concentrator **160** with one concave trough shaped reflective optical surface **38**, and its support system (e.g., support cables **30**, trolley attachment **31**, plate **32**, and translational tracking cable **33** similar to those described in relation to FIG. 7A and the assembly **37** as described in relation to FIG. 7C).

[0109] FIGS. 7E-7J illustrate various designs for optical surfaces of double and singleton secondary concentrators, such as those described in relation to FIGS. 7A-7D. The optical surfaces, for example, can be saw-tooth contoured and operationally-reflective.

[0110] FIGS. 7E-7F, for example, illustrate designs for optical surfaces of double secondary concentrators. FIG. 7E provides an illustration (in 2D cross section) of an embodiment for the optical surfaces **38**, **39** of a double operationally-reflective secondary concentrator, such as the Type 1 secondary concentrator **154**, the Type 2 secondary concentrator **156**, or the Type 3 secondary concentrator **158**, as shown in FIGS. 7A, 7B, and 7C respectively. Each of the two optical surfaces **38**, **39** are saw-tooth contoured and form a "V" over all shape. FIG. 7F provides an illustration (in 2D cross section) of an alternative embodiment for the optical surfaces **38**, **38** of a

double operationally-reflective secondary concentrator, such as the Type 1 secondary concentrator **154**, the Type 2 secondary concentrator **156**, or the Type 3 secondary concentrator **158**, as shown in FIGS. 7A, 7B, and 7C respectively. Each of the two optical surfaces **38**, **39** are saw-tooth contoured and form a “T” over all shape.

[0111] The number, dimensions, and placement of the individual teeth of the saw-tooth designs illustrated in FIGS. 7E-7F can vary depending upon implementation. Although the saw-tooth design of the first optical surface **38** and the second optical surface **39**, as illustrated in each embodiment respectively, appear to be substantially identical, in other implementations the first optical surface **38** can include a different saw-tooth design than that of the second optical surface **39**.

[0112] FIGS. 7G-7J illustrate designs for optical surfaces of singleton secondary concentrators, such as the Type 4 secondary concentrator described in relation to FIG. 7D. FIG. 7G, for example, provides an illustration (in 2D cross section) of an embodiment for the optical surface **38** of a singleton operationally-reflective secondary concentrator where the optical surfaces is saw-tooth contoured and forms an upside down “L” over all shape.

[0113] FIG. 7H provides an illustration (in 2D cross section) of an embodiment for the operationally-reflective optical surface of a singleton secondary concentrator where the optical surface **38** has saw-tooth contouring and is angled from the vertical. The optical surface **38**, for example, has a reflective front surface. FIG. 7I provides an illustration (in 2D cross section) of an alternative design for the operationally-reflective optical surface of a singleton secondary concentrator, where the optical surface **38** has saw-tooth contouring and is angled from the vertical, similar to the design illustrated in FIG. 7H. The design of FIG. 7I, however, has a refractive interior **15** and a reflective back surface **16**. An alternative embodiment of optical surfaces of secondary concentrators makes use of only a purely refractive optical surface so it is operationally-reflective.

[0114] In certain embodiments, the optical surface of a secondary concentrator is designed to be operationally-refractive for generally eastward-facing optical surfaces. For example, the operationally-refractive eastward-facing surface can direct radiation from the east to the west. Conversely, if the operationally-refractive optical surface faces generally west, the optical surface can direct radiation from the west to the east. As shown in FIG. 7J (in 2D cross section) a purely refractive optical surface **38** of a singleton secondary concentrator (e.g., including a refractive interior **15**) has saw-tooth contouring and is angled from the vertical.

[0115] Although described in relation to singleton secondary concentrators, the optical surface options described in relation to FIGS. 7I and 7J, in some embodiments, can be implemented upon the optical surfaces of double secondary concentrators.

[0116] FIG. 7K illustrates a secondary concentrator **162** with two concave trough shaped reflective optical surfaces **38** and **39**, where each end has a two trolley attachments **31** to one support cable **30**. The secondary concentrator **162** also includes the plate **32** and translational tracking cable **33** similar to those described in relation to FIG. 7A.

[0117] FIG. 7L illustrates a secondary concentrator **164** with two concave trough shaped reflective optical surfaces **38** and **39**, where each end has a four trolley attachments **31** to two support cables **30**. For example, two upper trolley attach-

ments **31** can be attached to an upper support cable **30**, while two lower trolley attachments **31** can be attached to a lower support cable **30**.

[0118] In some embodiments, the secondary concentrators use a heat radiator system, where linear radiating heat fins are affixed on their backside, to prevent the secondary concentrator from over heating.

[0119] In certain embodiments, the reflective optical surfaces of secondary concentrators make use of polished aluminum, which has the one of the highest known reflectance ratings of any metal in the far IR (e.g., 3000-10000 nanometer) and UV (e.g., 200-400 nanometer) frequency ranges. In alternative embodiments, the reflective optical surfaces of secondary concentrators make use of various coatings depending on the targeted frequency range of the solar concentrated radiation to be concentrated. For solar concentration applications in the near infrared (IR) frequency ranges (e.g., 700-3000 nanometers), a combination of one or more metallic films composed of aluminum, silver, gold, and/or copper, or a combination of these can be used, optionally with protective overcoats. For applications in the VIS (visible) range (e.g., 400-700 nanometers), some embodiments use aluminum, silver, and/or tin, or a combination of thereof, optionally with protective overcoats. The protective overcoats, for example, can consist of multilayer dielectric films such as disilicon trioxide (Si_2O_3), SiO and/or MgF_3 .

Secondary Concentrator Deployment

[0120] In certain embodiments, the support cables are kept taut such that the support cables appear essentially horizontal, at a fixed height. This implies that the focal planes of all the primary concentrators connected to the support cables can be held substantially co-planar and horizontal, at a fixed height above the plane, so the focal line of all primary concentrators remain at substantially a fixed distance above the primary concentrator at all times of the day. FIG. 8A is an illustration of an example of an east-west row of Type 1 secondary concentrators **154**, suspended by support cables **30** that appear horizontal, and attached by trolley attachments **31** to allow for coordinated west to east translational tracking.

[0121] In some embodiments, the support cables are not quite horizontal. Even the strongest cables will slightly droop due to gravity; in particular, cables of uniform thickness in the presence of gravity are known to droop to form catenary curves, whose curvature and slope, for example, can depend on the structural properties of the support cables and the force applied to them. This gravity-induced catenary curvature can be significant enough to affect optical design. Pulling the support cables extremely taut to avoid this affect on optical design may not be feasible or cost effective. FIG. 8B is an illustration of an east-west row of Type 1 secondary concentrators **154**, suspended by support cables **30** that slightly droop to form a catenary curve.

[0122] Furthermore, support poles and/or stabilization lines may affect the curvature and height of support cables. FIG. 8C is an illustration of an example of an east-west row of Type 1 secondary concentrators **154**, suspended by support cables **30** by trolley attachments **31**, with additional attached sidelines **41** on the support cables **30** used to decrease the support cable's displacement from translational wind force. The sidelines **41**, in some implementations, have a side affect of slightly vertically displacing the support cables from the horizontal. Also, support poles and/or stabilization lines can optionally provide a means for intentionally inducing height

changes along the length of these east-west support cables **30**, so as to be able to change the angle of the direction concentrated solar radiation is directed from the secondary concentrators **154** to the receivers during west to east tracking. This, in turn, can impact the design of the optical surfaces of the primary concentrators, which may be slanted in the east-west axis to insure the slant of their focal planes conforms to the slant of the segments of the support cables above them.

[0123] In some embodiments, changing the curvature and height of the east-west support cables (e.g., via support poles and/or stabilization lines) provides for vertical tracking changes dependent on the east-west position x by inducing height changes (e.g., with the height of the support cables being lower on the extreme east and west sides of the collection field) along the length of these east-west support cables. This can be used, for example, to change the angle that concentrated solar radiation is directed from the secondary concentrator to the receivers during east-west tracking. An example is provided below in relation to FIGS. **17B-17E**. Height changes of the support cables can impact the design of the optical surfaces of the primary concentrators which provide for the east-west slant of their focal plane being approximately the same as the east-west slant of their support cables.

[0124] In some embodiments, a north-south row of secondary concentrators may be joined along their longitudinal axis to allow for coordinated translational tracking. In some embodiments, a row of secondary concentrators can be joined along their longitudinal axis to allow for coordinated rotational tracking. In further embodiments, a row of secondary concentrators can be joined along their longitudinal axis to allow for coordinated translational and rotational tracking. In certain embodiments, a linked north-south row of secondary concentrators, suspended by cables in a way that allows neither rotational nor elevational travel, can be joined along their longitudinal axis to allow for coordinated west to east translational tracking. In some embodiments, a linked north-south row of Type 2 secondary concentrators, suspended by horizontal cables, can be attached in a way that allows elevation but not rotation and joined along their longitudinal axis to allow for coordinated tracking. In other embodiments, a linked north-south row of Type 1 secondary concentrators, suspended by horizontal cables, may be attached in a way that allows rotation but not elevation and joined along their longitudinal axis to allow for coordinated tracking.

[0125] FIG. **9** illustrates a solar collection field of bidirectional primary concentrators, with associated secondary concentrators. The secondary concentrators, as illustrated, are supported via support cables **30** and support poles.

[0126] In general terms, the array of secondary concentrators are positioned depending on the geometry of the solar collection field so that they can direct concentrated solar radiation to one or more receivers without obstructing one another. As illustrated in FIG. **10**, for the given east-west position x of an optical surface **38a** of a first secondary concentrator, let $\Psi = \Psi(x)$ be a vertical angle **50** from the horizontal that concentrated solar radiation can be directed in the east-west direction, without obstruction, from the secondary concentrator to a vertical midline of the receiver. Observe that the distance between the first secondary concentrator and a neighboring secondary concentrator in the east-west direction (as illustrated by a second optical surface **38b**) is w , where w is an east-west width **51** of each primary concentrator. Let v be a maximum vertical dimension **52** of each sec-

ondary concentrator. The $\tan(\Psi(x))$ is lower bounded by v/w , so $\Psi(x)$ is lower bounded by $\arctan(v/w)$.

[0127] The primary concentrators concentrate the primary concentrated solar radiation entering the secondary concentrators by a significant factor, for example a factor of between 10 and 30, preferably between 15 and 25. Hence optical design of the secondary concentrators can take into account the corresponding increase in optical intensity. In particular, the optical surfaces of the secondary concentrators can be designed to be able to sustain high heat flux. The optical surfaces of each secondary concentrator can be constructed from highly reflective metallic sheeting. The optical surfaces of the secondary concentrators, for example, can be made from aluminum, which has a high melting point of 660.32°C ., is relatively inexpensive, has a relatively low density (2.70 g per cubic cm), and can be polished to approximately 75-99%, preferably 85-97%, more preferably 90-95% spectral reflectance. In certain embodiments, the spectral reflectance of the secondary concentrators is approximately 90%. The protective coating of the optical surfaces of the secondary concentrators can include a multilayer dielectric film overcoat.

Weather Resilience in Secondary Concentrator Design

[0128] FIGS. **11A-11D** and **12A-12D** illustrate various embodiments of secondary concentrators modified for weather resilience. The secondary concentrators as illustrated, for example, can be opened for typical use or closed for protection from inclement weather conditions.

[0129] FIGS. **11A** (open position) and **11B** (closed position) show (in 2D cross section) an alternative embodiment of a singleton secondary concentrator with a single concave trough shaped optical surface **38** equipped with a pivot **53** allowing the singleton secondary concentrator to be folded into a protective clamshell position. In other embodiments, two or more pivots **53** can be positioned along the optical surface **38**.

[0130] FIGS. **11C** (open position) and **11D** (closed position) show (in 2D cross section) an alternative embodiment of a singleton secondary concentrator with one optical surface **38** capable of being folded into a protective position using a pivot **53**. The optical surface **38**, as illustrated, is saw-tooth contoured and angled from the vertical. In other embodiments, the singleton secondary concentrator can be equipped with two or more pivots to allow it to be multiply folded into a protective position.

[0131] FIGS. **12A** (open position) and **12B** (closed position) show (in 2D cross section) an alternative embodiment of a double secondary concentrator with two concave trough shaped optical surfaces **39**, **39** and a pivot **53** allowing the double secondary concentrator to be folded into a protective clamshell position. In other implementations, the double secondary concentrator can include two or more pivots **53** to allow it to be multiply folded into a protective position.

[0132] FIGS. **12C** (open position) and **12D** (closed position) show (in 2D cross section) an alternative embodiment of a double secondary concentrator with two optical surfaces **38**, **39** which are saw-tooth contoured and form a V. The double secondary concentrator, as illustrated, is equipped with a pivot **53** to allow it to be folded into a protective position. In other implementations, the double secondary concentrator can include two or more pivots **53** to allow it to be multiply folded into a protective position.

[0133] In some embodiments, structural supporting members can be affixed to the backside of the secondary concentrators for stability in winds. In alternative embodiments, the solar concentration system includes an apparatus for protection from inclement weather, such as apparatus for lowering the secondary concentrators to a sheltered location on the ground.

[0134] The secondary concentrators are typically more complex than the primary concentrators, but they are also generally far smaller and far less massive than the primary concentrators (e.g., due the primary concentrator's initial concentration of the solar energy). The secondary concentrators are often modest when apportioned to the far larger area of the primary concentrator that each secondary concentrator services. The aluminum optical surface of the secondary concentrators can have a reflectance of approximately 90%, giving the secondary concentrator a high solar efficiency.

[0135] In certain embodiments, each secondary concentrator has one or two reflective optical surfaces, concave in cross section, which have a three-dimensional concave trough shape. In alternative embodiments, the secondary concentrators include refractive as well as reflective elements and are saw-tooth in cross section. In other embodiments, the secondary concentrators are parabolic in cross section. Each of these optical surfaces can function as a linear concentrator. That is, the optical surfaces can focus parallel incoming radiation into a line. The (receiver-directed) focal line of an optical surface of the secondary concentrator, for example, is the hypothetical line at which parallel rays emitted from the receiver would be focused by that optical surface of the secondary concentrator. By the principal of linear optical system reversibility, this implies that radiation departing at any angle from the (receiver-directed) focal line of the secondary concentrator is directed to the receiver. At any given time of the solar day, the secondary concentrator is preferably positioned so its (receiver-directed) focal line coincides with the focal line of the associated primary concentrator.

Secondary Concentrator Positioning

[0136] The illustrations FIG. 13A (in 2D cross section) and FIG. 13B (in 3D) together show example positioning of the secondary concentrator 5 so that its (receiver-directed) focal line 20 coincides with the focal line of the bidirectional primary concentrator 3b.

[0137] The east-west support cables may not be strictly horizontal, such that each east-west row of secondary concentrators hanging on the support cables may vary in height above the primary concentrators. This can impact the design of the optical surfaces of the primary concentrators. For example, as shown in FIG. 13C, the focal plane of the bidirectional primary concentrators 3b may have an east-west slant which approximates the local slant of the support cables above them, even if the bidirectional primary concentrators 3b have no north-south slant.

[0138] In some embodiments, each of the east-west support cables is substantially identical in shape. This can impact the design of the optical surfaces of the primary concentrators. In a particular example, each pair of primary concentrators having the same east-west position will have co-planar focal planes, and hence these primary concentrators can have the same shape optical surfaces.

[0139] In certain embodiments, the focal line of the bidirectional primary concentrator 3b is parallel to the upper portion of the surface of the bidirectional primary concentra-

tor 3b, and runs north-south. Consider a single cylindrical secondary concentrator that tracks west to east in such a way that its (receiver-directed) focal line coincides with the focal line of the bidirectional primary concentrator 3b. Let the extended focal line be the line extending the focal line segment over the collection field to the north and south. Over the day, the extended focal line of the bidirectional primary concentrator 3b moves substantially from west to east. The illustrations in FIGS. 14A-C together show in 2D cross section various example positions of the extended focal line of the bidirectional primary concentrator 3b over the day.

[0140] The eastward facing optical surface 38 of the secondary concentrator is actively concentrating primary concentrated solar radiation 4 at all times of the day prior to a time t_e and the westward facing optical surface 39 of the secondary concentrator is actively concentrating primary concentrated solar radiation 4 at all times of the day prior to a time t_w . This allows some optical surface 38, 39 of the secondary concentrator to receive and concentrate all primary concentrated solar radiation 4 from the bidirectional primary concentrator 3b during those two (early and late) time periods.

[0141] Let t_e be the latest time when the eastward facing optical surface 39 of the secondary concentrator receives all the primary concentrated solar radiation from the bidirectional primary concentrator 3b. Between the start time t_0 to this time t_e , all the primary concentrated solar radiation 4 from the bidirectional primary concentrator 3b is concentrated to (and has a direct unobstructed path to) that eastward facing optical surface 38 of the secondary concentrator. As seen in FIG. 14A, a position 61 of the focal line at earliest time t_e illustrates a point in time when the eastward facing optical surface 38 of the secondary concentrator receives all the primary concentrated solar radiation 4 from the bidirectional primary concentrator 3b.

[0142] Also t_w be the earliest time when the westward facing optical surface 39 of the secondary concentrator receives all the primary concentrated solar radiation 4 from the bidirectional primary concentrator 3b. Between the time t_w , and the ending time t_3 , all the primary concentrated solar radiation 4 from the bidirectional primary concentrator 3b is concentrated to (and has a direct unobstructed path to) that westward facing optical surface 39 of the secondary concentrator. As seen in FIG. 14B, a position 63 of the focal line at earliest time t_w illustrates a point in time when the westward facing optical surface 39 of the secondary concentrator receives all the primary concentrated solar radiation 4 from the bidirectional primary concentrator 3b.

[0143] Let $t_m = (t_e + t_w)/2$ be the middle of the time period from t_e and t_w . FIG. 14C illustrates (in 2D cross section) a combined illustration of the position of the secondary concentrator at times t_e , t_m and t_w , where the position 61 of the focal line at the latest time t_e when the eastward facing optical surface 38 of the secondary concentrator receives all the primary concentrated solar radiation 4 from the bidirectional primary concentrator 3b, a position 62 of the focal line at a time t_m in the middle between times t_e and t_w , and the position 63 of the focal line at earliest time t_w when the westward facing optical surface 39 of the secondary concentrator receives all the primary concentrated solar radiation 4 from the bidirectional primary concentrator 3b.

[0144] FIGS. 15A-15D show in 2D cross section an example daily schedule used for positioning one of the secondary concentrators. The drawings in each figure show only the optical surface 38 of the secondary concentrator that is

currently functioning to direct primary solar radiation from the bidirectional primary concentrator **3b** to one of the receivers **7**. This is the active optical surface. The bidirectional primary concentrator **3b** and the primary concentrated solar radiation **4** are also shown in each figure.

[0145] FIG. **15A** illustrates in 2D cross section the start time t_0 of the daily tracking, when the active optical surface **38** of the secondary concentrator faces east.

[0146] Note that at times between t_e and t_w some of the primary concentrated solar radiation **4** from the bidirectional primary concentrator **3b** is directed from west to the east, and some is directed from the east to west. In some embodiments, at a certain time period during the day the solar concentration system executes an east-west switch of the secondary concentrator, where the currently active optical surface of the secondary concentrator switches from an optical surface facing generally east to an optical surface facing generally west. In alternative embodiments, the active optical surface may be the same, but re-oriented, in the two respective time periods. Let the time t_1 of starting an east-west switch be a time considerably after the start time t_0 and (just) prior to time t_m ; likewise, let the time t_2 to end the east-west switch be a time (just) after t_m and considerably prior to the end time t_3 , so $t_m = (t_1 + t_2)/2$ (for example, let $t_2 = 2t_m - t_1$). FIG. **15B** and FIG. **15C**, for example, can be looked to as an illustration in 2D cross section of the east-west switch. FIG. **15B** illustrates the start of an east-west switch at the time t_1 when the active optical face **38** of the secondary concentrator is facing generally east and an extended focal line **71** of the secondary concentrator is just west of overhead the middle of the bidirectional primary concentrator **3b**. FIG. **15C** illustrates in 2D cross section the end of an east-west switch at the time t_2 when the active optical face **39** of the secondary concentrator is facing generally west and an extended focal line **72** of the secondary concentrator is just east of overhead the middle of the bidirectional primary concentrator **3b**.

[0147] FIG. **15D** illustrates in 2D cross section the end time t_3 of the daily tracking when the active optical surface **39** of the secondary concentrator faces west.

[0148] The daily schedule of the secondary concentrator's tracking, in time progression, is given by the illustrations shown in FIG. **15A** (start time t_0), FIG. **15B** (begin time t_1 of east-west switch), FIG. **15C** (finish time t_2 of east-west switch), and FIG. **15D** (end of day time t_3). After the end of the solar day, the tracking movement can be reversed to allow the secondary concentrator to be repositioned to the start of day position (e.g., the position illustrated in FIG. **15A**).

[0149] There will be some leakage loss of concentrated solar radiation from the bidirectional primary concentrator **3b** if the secondary concentrator is unable to capture and further direct the primary concentrated solar radiation **4** to the receiver **7** at times between t_w and t_e , but there would be no such loss prior to t_w and after t_e . In certain embodiments, the solar concentration system minimizes leakage loss by maximizing the ratio of the height of the primary concentrator focal line to the east-west width of the bidirectional primary concentrator **3b**. This, for example, can work to minimize the time duration between t_w and t_e when there can be leakage loss. In other embodiments, the solar concentration system can work to minimize leakage loss by constructing the bidirectional primary concentrator **3b** so that at solar noon, the extended focal line of the bidirectional primary concentrator **3b** is as far as possible to the east or west of the center of the bidirectional primary concentrator **3b**. This implies, for

example, that the focal plane of the bidirectional primary concentrator **3b** is similarly slanted either east or west, which also may entail (since the east-west slant of the focal plane and corresponding section of the support cable are likely similar to allow the focal lines of the primary and secondary concentrator to coincide) slanting the support cable above the bidirectional primary concentrator **3b** at a similar angle. This, for example, insures that the time period between t_w and t_e can be shifted away from solar noon, the period of most intense direct solar irradiation.

[0150] In certain embodiments, the concentration system is comprised of the primary and secondary concentrators, and the geometry of the tracking means can be summarized in the following:

[0151] (a) At any given time, each north-south strip of primary concentrators has a single extended focal line, and through the course of the day, that extended focal line moves from west to east.

[0152] (b) The currently active face of the secondary concentrator substantially faces the primary concentrated radiation from the primary concentrator, and

[0153] (c) The (receiver-directed) focal plane of a currently active face of the secondary concentrator substantially coincides with the focal line of the primary concentrator.

[0154] The concentration system, in some implementations, includes a tracking system and, optionally, a control system to provide for the positioning of various elements of the concentration system, such as the secondary concentrators and receivers, to increase the efficiency of the collection of solar irradiation throughout a solar day. For example, the tracking system can position and orient the secondary concentrators to increase the effectiveness of solar irradiation collection by the receivers by aligning the active optical surface of each secondary concentrator proximate to the focal line of each respective primary concentrator. Similarly, the tracking system can adjust the positioning of each secondary concentrator, in another example, to aim the secondary concentrated radiation, reflected by the secondary concentrators, substantially at a centralized receiver.

[0155] The tracking system, in some embodiments, includes a control system that determines adjustment criteria and signals positioning equipment, such as motors and actuators, to fine tune the positioning of the various system elements. In some examples, the control system can issue control signals to cause an adjustment in the positioning of secondary concentrators, centralized receivers, or components of a tensile structure such as suspension cables used to suspend the secondary concentrators. The control signals may be digital or analog depending on the type of motors and actuators used in a particular system.

[0156] In some embodiments, the tracking system includes an open-loop control system with an internal clock and a set of pre-calculated motor control parameters. For example, based upon a table lookup, at specific times throughout a solar day, the open-loop control system can effect the repositioning of one or more of the elements of the solar concentrator system. The table of parameters, in some implementations, can include variations based upon day of the year. In some implementations, information retrieved from the table of parameters can be used to calculate adjustments based upon system settings. For example, based upon a particular geographic location of the solar concentrator system (e.g., latitude, longitude, GPS coordinates, altitude, etc.) the positioning adjustments can vary.

[0157] In other embodiments, the tracking system can function with a closed-loop control system relying on both pre-derived calculated (e.g., based upon astronomical equations) as well as external monitoring devices. The external monitoring devices, for example, can include one or more sensors detecting current conditions affecting the solar concentrator system. In some examples, the external monitoring devices can sense the amount of solar energy directed to the centralized receivers (e.g., using one or more solar energy sensors), an external temperature (e.g., as measured by one or more thermometers positioned on the solar concentrator system), wind speed and wind direction (e.g., using wind speed indicators positioned at one or more locations on the solar concentrator system), or solar irradiance intensity and solar irradiance direction (e.g., as determined by one or more directional photosensors positioned on the solar concentrator system). The closed-loop control system, in some implementations, includes a table of look-up data associated with one or more of these monitored values. For example, based upon a particular wind speed a direction, the closed-loop control system may determine that an adjustment in positioning of one or more solar concentrators may be advisable. In some implementations, upon reaching such a determination, the control system employs post-processing to determine appropriate control signals to use for manipulating the system elements (e.g., actuators, motors, etc.).

[0158] The tracking and control system, in alternative embodiments, can actively monitor solar irradiation received by the various elements of the solar concentrator system. For example, based upon a measured position and intensity of the sun, the tracking and control system can automatically adjust the positioning of various elements of the solar concentrator system to optimize collection of concentrated solar radiation energy.

[0159] In some implementations, the tracking and control system periodically makes adjustments to one or more of the elements of the solar concentrator system. For example, a timer can be used in conjunction with the internal clock to determine a schedule upon which the positions of the elements of the solar concentrator system may be adjusted. In other implementations, the tracking and control system continuously provides readjustments, for example through control signals to appropriate motors and actuators, to position and orient the secondary concentrators, allowing the solar concentrator system to dynamically compensate for changes in monitored conditions so as to optimize the solar energy directed to the centralized receivers.

[0160] In a closed-loop system, in some embodiments, feedback control can be provided by conventional closed-loop control theory methods which, for example, determine the dynamic control of the solar concentrator system based on a combination of error signals, measured output, and desired output. Examples of feedback control theory methods include proportional-integral-derivative (PID) mechanisms, which determine an output by an integral calculation, and time-domain mechanisms, which model the problem in state space and solve a first-order differential equation modeling the physical system.

[0161] In some embodiments, the relationship between the primary and secondary concentrators can be achieved by west to east translational tracking of the secondary concentrator with possibly some form of vertical or rotational movement to provide compensation for the change in vertical angle to

receivers during translational tracking, as well as some sort of mechanism for the east-west switch previously described.

[0162] In certain embodiments, the translational and rotational movements of each north-south row of secondary concentrators can be substantially the same, so the secondary concentrators of each north-south row are joined and move on a common axis.

[0163] Some embodiments of a tracking apparatus only provide translational tracking, without rotation of the secondary concentrators. The east-west switch, for example, can be achieved by simply moving from the portion of the secondary concentrator facing generally east to the other portion facing generally west.

[0164] In some embodiments, the secondary concentrator is positioned a considerable distance from the receivers, so the short daily translational movements by the secondary concentrator are less likely to significantly affect the angles of direction from the secondary concentrators to each receiver.

[0165] Certain embodiments of the solar concentration field use a Type 1 secondary concentrator, which is a non-rotating, non-elevating doubled secondary concentrator. The doubled secondary concentrator, for example, has two reflective optical surfaces, positioned facing generally east and west, respectively. The east facing optical surface can be used from the start of the day until the initiation of the east-west switch and, after having executed the east-west switch, the secondary concentrator can be shifted slightly west (e.g., by temporally increasing the rate of west to east translational tracking movement) to switch the incoming primary concentrated solar radiation from the east optical surface to the west optical surface.

Tracking Apparatus 1: Non-Rotating Non-Elevating Doubled Secondary Concentrator

[0166] In some embodiments, the secondary concentrators track by west to east translational movements as illustrated in FIGS. 16A-16D. FIG. 16A illustrates Tracking Apparatus 1 at the start time t_0 of the daily tracking, FIG. 16B illustrates Tracking Apparatus 1 at time t_1 , FIG. 16C illustrates Tracking Apparatus 1 at time t_2 , and FIG. 16D illustrates Tracking Apparatus 1 at the end time t_3 of the daily tracking. During the time interval from t_0 to t_1 , as illustrated by FIGS. 16A and 16B, the doubled secondary concentrator is tracked translationally from west to east at a fixed rate, so that all times during this period the east optical surface 38 of the doubled secondary concentrator is positioned so that its (east) (receiver-directed) focal line 70 substantially coincides with the focal line of the bidirectional primary concentrator 3b such that the east optical surface 38 further concentrates the incoming primary concentrated radiation 4 from the bidirectional primary concentrator 3b and directs it to the east receiver 7. During the east-west switch time interval from t_1 to t_2 , as illustrated by FIGS. 16B and 16C, the rate of translational tracking movement from west to east is increased, so as to move the doubled secondary concentrator west. This increased rate is set so that at time t_2 , the west optical surface 39 of the doubled secondary concentrator is positioned so that its (west) (receiver-directed) focal line 72 coincides with the focal line of the bidirectional primary concentrator 3b. During the time interval from t_2 to t_3 , as illustrated by FIGS. 16C and 16D, the doubled secondary concentrator is again tracked translationally from west to east at a fixed rate, so that at substantially all times during this period the west optical surface 39 of the doubled secondary concentrator

is positioned so that its (west) (receiver-directed) focal line **72** coincides with the focal line of the bidirectional primary concentrator **3b**, and so it further concentrates the incoming primary concentrated radiation **4** from the bidirectional primary concentrator **3b** and directs it to the west receiver **7**. After the end of the solar day, the tracking movement is reversed to allow the secondary concentrator to be repositioned to the start of day position (e.g., as illustrated in FIG. **16A**).

[0167] Dynamic effects, from variations in temperature and wind, may induce vertical and rotational oscillations and misalignments of the secondary concentrators and their support cables and posts, as well as transverse movements along the length of the support cables. In some embodiments, for compensation of these dynamic movements, there is an open loop control system for executing various corrections which may include secondary concentrator tracking corrections and cable tension corrections. Each correction, for example, can be based on observed variations of one or more of the following observables: wind magnitude, wind direction, temperature, solar intensity and solar angle.

[0168] During certain (e.g., early and latest) periods of the solar day, off-axis aberrations of the secondary concentrators may widen the line focus to the receiver, reducing the performance of the system. In certain embodiments, means are provided for reducing off-axis aberrations of the secondary concentrators, including optimizing the height of the secondary concentrators above the primary concentrators and optimizing the aperture width of the secondary concentrators. In certain embodiments, means are provided for compensation of off-axis aberrations of the secondary concentrator, for example by widening the absorbing region or by movement out of the horizontal plane.

[0169] In certain embodiments, the solar radiation concentrated by the primary and secondary concentrators is directed to one or more receivers. In certain embodiments, there are two receivers that collect the concentrated solar radiation, one located to the east of the collection field and one located to the west of the collection field. In some embodiments, the receiver located in the west collects primarily in the AM (prior to solar noon) concentrated solar radiation, the receiver located in the east collects primarily in the PM (after solar noon) concentrated solar radiation.

[0170] The optical surface of the receiver acts as an absorbing region that absorbs the concentrated solar radiation incoming from the secondary concentrators. In certain embodiments, the absorbing region of each receiver is rectangular shaped running north-south.

[0171] In some embodiments, the absorbing region of each of the receivers is positioned at a height above the ground larger than the height of the secondary concentrators, so that the concentrated solar radiation directed to the receivers comes from an angle below them. To insure the concentrated solar radiation from each secondary concentrator is directed upward to one of the receivers without obstruction from other secondary concentrators, in some implementations the receivers are positioned sufficiently high and the consecutive secondary concentrators are sufficiently separated in the east-west direction.

[0172] The receiver can include a medium for transport and at least temporary storage of the absorbed solar energy. In some embodiments, the energy storage media is a bulk thermal storage medium such as liquid sulfur, molten salt (e.g., saltpeter molten salt which is approximately 60% sodium

nitrate and approximately 40% potassium nitrate), fluoride-salt, and/or mineral oil (e.g., Therminol VP-1 synthetic oil). In alternative embodiments, the energy storage media includes a phase-change storage medium (such as water to and from steam, or melting and solidifying salts).

[0173] Each receiver has a structural housing. The structural housing of the receiver serves to support and protect the other portions of the receiver.

[0174] In certain embodiments, within the absorbing region of each of the receiver are positioned a linear array of receiver tubes running north-south. Within each of the receiver tubes, for example, there is a metallic tube containing material used for heat storage (e.g., either bulk heat storage or phase-change heat storage material). Surrounding the interior metallic tube, in some implementations, is a vacuum gap providing insulation. On the exterior of each receiver tube, in some embodiments, is a borosilicate glass tube with an anti-reflective, anti-abrasion coating that has high radiation absorbance and low emittance. The borosilicate glass, for example, offers the same expansion coefficient as the melted down metal. This exterior can allow a high proportion of the solar radiation to penetrate to the interior metallic tube of the receiver and heat the heat transfer material within. For example, current receiver technology such as the SCHOTT PTR 70 Receiver by SCHOTT Solar of Albuquerque, N. Mex. allows over 95% absorbance and less than 10% emittance.

[0175] Through the course of the year, the north-south angle of the sun deviates to both the north and the south from its equinox position, for example by approximately 23.5 degrees in the US Southwest. Therefore, the north-south position of the solar radiation concentrated on a receiver can change through the year. In certain embodiments, the receivers are immobile, but their absorbing area is sufficiently long in north-south direction to include the entire range of positions that concentrated solar radiation is directed from over the year. This, for example, can insure the receivers can collect the concentrated solar radiation throughout the year.

[0176] In some embodiments, the secondary concentrator has only one optical surface, and it executes an east-west switch by making, at some period in the day, a change in orientation from facing generally east to facing generally west.

[0177] In certain embodiments, all concentrated radiation is directed toward one centralized receiver.

[0178] In alternative embodiments, the compensation for the change in Ψ (the vertical angle from horizontal to the receiver) during the secondary concentrator's translational movement, is determined by calculating Ψ as the smallest vertical angle from the horizontal that radiation that can be directed, without obstruction, from the secondary concentrator to the receiver.

[0179] Recall that, as described in relation to FIG. **10**, Ψ was defined to be the secondary concentrator's vertical angle **50** from the horizontal to the midline of the receiver **7**. Turning now to FIG. **17A**, if R is the height of the receiver **91** above the optical surface **38** of the secondary concentrator and D is the horizontal distance **92** between the optical surface **38** of the secondary concentrator and the receiver **7**, then $\tan(\Psi) = R/D$, so $\Psi = \arctan(R/D)$. Observe that Ψ is constant for every north-south strip of primary concentrators, but can vary along east-west strips of primary concentrators. In particular, Ψ decreases with the distance of the optical surface **38** of secondary concentrator to the currently used receiver **7**. At start time t_0 , Ψ has an initial relatively small angle Ψ_0 of

concentrated solar radiation directed toward the east receiver 7. At time t_1 , the concentrated solar radiation is directed at a higher angle Ψ_1 toward the east receiver 7. At time t_2 the concentrated solar radiation is directed at a reset angle Ψ_2 toward the west receiver 7. At the end time t_3 the solar radiation is directed at a somewhat lower angle Ψ_3 toward the west receiver 7.

[0180] Further note that the angle Ψ is at a minimum angle on a north-south strip roughly in the middle of the solar collecting field. Also recall, as described in relation to FIG. 10, that in order that the direct path of concentrated radiation (directed from the secondary concentrator to the receiver) can avoid being obstructed by other secondary concentrators, the angle Ψ should be greater than $\arctan(v/w)$, where v is the width of the secondary concentrator and w is the east-west width of the primary concentrator. This provides an absolute minimum to the value that the angle Ψ may have.

Tracking Apparatus 2: Vertical Tracking of a Doubled Reflective Secondary Concentrator

[0181] In certain embodiments, vertical translations of the secondary concentrators can be used to change the direction of concentrated radiation to the receiver, thus providing an apparatus for the changes in angle Ψ toward the receiver during west to east translational tracking. FIG. 17B-17E show illustrations of example distinct times throughout the day showing a vertical position 93 of the active optical surface 38, 39 of a doubled secondary concentrator used to compensate for the rotation of the secondary concentrator due to the change in angle Ψ during eastward translational movement. These periodic vertical translations of the secondary concentrator, for example, can be used to improve its performance. As shown, the secondary concentrated solar radiation 6 directed toward the east receiver 7 is received at increasing slope prior to the east-west switch. Conversely, the secondary concentrated solar radiation 6 directed toward the west receiver 7 is received at a decreasing slope after the east-west switch. For simplicity, the figures illustrate only the currently active optical surface 38, 39 of the secondary concentrator, and thus appear as only a singleton secondary concentrator, although the same optical principals hold for the case of a doubled secondary concentrator.

[0182] FIG. 17B illustrates a first position, at the start time t_0 , with the initial slightly elevated vertical position 93 y_0 to insure the secondary concentrated solar radiation 6 is directed at an initially relatively small angle Ψ_0 toward the east receiver 7. FIG. 17C illustrates a second position, at time t_1 , with the further elevated vertical position 93 y_1 to insure the secondary concentrated solar radiation 6 is directed at a higher angle Ψ_1 toward the east receiver 7. Since the secondary concentrator has moved east somewhat closer to the east receiver 7, the vertical position 93 y and the angle Ψ are increased. FIG. 17D illustrates a third position at time t_2 with a reset elevated vertical position 93 y_2 to insure the secondary concentrated solar radiation 6 is directed at a reset angle Ψ_2 toward the west receiver 7. The resetting of the vertical position 93 y and the angle Ψ , for example, is due to the east-west switch. FIG. 17E illustrates a fourth position, at the end time t_3 , with reduced vertical position 93 y_3 to insure the secondary concentrated solar radiation 6 is directed at a reduced angle Ψ_3 toward the west receiver 7. Since the secondary concentrator has moved somewhat further away from west receiver 7, the vertical position 93 y and the angle Ψ are reduced. FIG. 17F provides a summary combined

illustration of the daily horizontal and vertical tracking movements with positions of the rotating doubled secondary concentrator over the day condensed into one figure.

[0183] The exact relationship between the values of the vertical position 93 y and the angle Ψ over the day, for example, depend in part on the configuration of the optical surfaces 38, 39 of the secondary concentrator.

[0184] In alternative embodiments, the secondary concentrators use guided cams for translational tracking. The cam systems, for example, can include disks or peg-like cams located at various radii to control the vertical or rotational movement of disks affixed to the ends the secondary concentrator. In some embodiments, the tracking for each north-south row of secondary concentrators is the same. For example, when a row of north-south secondary concentrators has the same tracking, the secondary concentrators can be coupled, and a single cam system can be used for each such north-south row.

[0185] Other alternative embodiments include various apparatus for tracking secondary concentrators. Like the Tracking Apparatus 1, the Tracking Apparatus 5 and 6 use only west to east translational tracking. The other Tracking Apparatus 2, 3, 4, and 7 make use of vertical elevation or rotational movements for tracking as well.

[0186] Tracking Apparatus 2 can use a single cam as an apparatus for inducing vertical translations to compensate for the change in angle Ψ during the secondary concentrator's east-west translational movement.

[0187] FIG. 17G illustrates an example of a Type 2 (elevating, non-rotating double) secondary concentrator 166 used in Tracking Apparatus 2, with a cam disk 32 directly attached to the secondary concentrator 166, cam guide 112, and cam peg 111. The cam guide 112 initially slants gently upward. The cam guide 112 can change its height abruptly for the east-west switch, since its height needs to be reset to allow for a reset angle Ψ_2 due to the east-west switch. Upon conclusion of the east-west switch, the cam guide 112 slants gently downward. The cam peg 111 is located approximately at the upper left position on the cam disk 32 in its initial position. The west to east translational tracking then forces the cam disk 32 (and therefore the secondary concentrator 166) to vertically elevate.

[0188] FIGS. 17H-17K show the example cam-based Tracking Apparatus 2, with illustrations at various distinct times throughout the day of the translational tracking of the non-rotating doubled secondary concentrator 166 as well as illustrations of the engaged cam guide 112 inducing vertical translations of the cam disk 32 and doubled secondary concentrator 166.

[0189] FIG. 17H illustrates Tracking Apparatus 2 at the start time t_0 of the daily tracking, with position of the engaged single cam guide 112 at the upper left position on the cam disk 32. The gentle upward slant of the cam guide 112 at this period, for example, causes the cam disk 32 to move slowly. This increases the angle Ψ to compensate for the eastward movement of the secondary concentrator 166 toward the east receiver.

[0190] FIG. 17I illustrates Tracking Apparatus 2 at time t_1 . Recall the east-west switch may induce an abrupt change in the angle Ψ (and hence a reset of vertical position y) since prior to the east-west switch the east receiver is used to determine the angle Ψ , and after the east-west switch the west receiver is used to determine the angle Ψ .

[0191] FIG. 17J illustrates Tracking Apparatus 2 at time t_2 . The gentle downward slant of the cam guide 112 at this period again makes the cam disk 32 move upward at a relatively slow rate. This decreases the angle Ψ to compensate for the continued eastward movement of the secondary concentrator 166 away from the west receiver.

[0192] FIG. 17K illustrates the position of the Tracking Apparatus 2 at time t_1 just after the east-west switch.

[0193] FIG. 17L provides a summary combined illustration of the daily movement of the cam-based rotational Tracking Apparatus 2, with positions of the engaged single cam guide 112 and doubled secondary concentrator 166 over the day condensed into one figure. After the end of the solar day, the cam-based tracking movement can be reversed to allow the secondary concentrator 116 and cam guide 112 to be reset to the start of day position.

[0194] In alternative embodiments, each of the two optical surfaces of the double secondary concentrator 166 are shaped and positioned appropriately, so that vertical position y_2 is substantially equivalent to vertical position y_3 and hence there is no required vertical elevation change during the east-west switch.

[0195] In alternative embodiments, the apparatus for the coordinated translational tracking is by the action of one or more motors located at along each east-west strip of primary concentrators. Individual motors coupled with gear systems, for example, can be used for vertical and/or rotational tracking. Since the tracking needs are substantially the same for each north-south row of secondary concentrators, these can optionally be coupled, and a single motor can be used for each such north-south row.

Tracking Apparatus 3 and 4: Rotational Tracking

[0196] Tracking Apparatus 3 and Tracking Apparatus 4 use rotational tracking. FIG. 18A illustrates an example used for defining a rotation angle 90 of counterclockwise rotation θ of the secondary concentrator: the rotation angle 90 θ can be considered as the counterclockwise angular difference between a ray going east and the normal from the center of reflectance of the eastward facing optical surface 38 of the secondary concentrator.

[0197] The Cartesian coordinate location of a point on a rotating and translating disk can be determined with the following equations: $\{x=v\theta+R \cos(\theta-\theta_0), y=R \sin(\theta-\theta_0)\}$, where the angle θ_0 is the starting angular position, β is the angular displacement, R is the distance from the point to the center of the disk, and v is the velocity. These equations can be used to govern the geometry of the cam guides. The cam disk is connected to the secondary concentrator, so that the secondary concentrator rotates with the cam disk (or, optionally, two or more cam disks).

[0198] For motivation of Tracking Apparatus 3 and 4, FIGS. 18B-18E provide illustrations of an example schedule of distinct times throughout the day of where rotation angle 90 θ of a doubled secondary concentrator can be used to compensate for the needed rotation of the secondary concentrator, thereby compensating for the change in angle Ψ during eastward translational movement and due to the east-west switch. Included are illustrations of the secondary concentrated solar radiation 6 directed toward the east receiver 7 at increasing angle 50 Ψ prior to the east-west switch; as well as illustrations of the secondary concentrated solar radiation 6 directed toward the west receiver 7 at decreasing rotation angle 90 Ψ after the east-west switch. For simplicity, the

figures illustrate only the currently active optical surface 38, 39 of the secondary concentrator, and thus appear as only a singleton secondary concentrator, although the principal is the same for the case of a doubled secondary concentrator.

[0199] FIG. 18B illustrates the relatively small angle of rotation θ_0 of the optical surface 38 of the secondary concentrator at the start time t_0 of the daily tracking, to insure the secondary concentrated solar radiation 6 is directed at relatively small initial angle 90 Ψ_0 toward the east receiver 7. FIG. 18C illustrates the increased angle of rotation θ_1 for optical surface 38 of the secondary concentrator at time t_1 just at the start of the east-west switch, to insure the secondary concentrated solar radiation 6 is directed at increased angle 50 Ψ_1 toward the east receiver 7. FIG. 18D illustrates the reset angle of rotation θ_2 at time t_2 at the end of the east-west switch, to insure the secondary concentrated solar radiation 6 is directed at reset angle 50 Ψ_2 toward the west receiver 7. FIG. 18E illustrates the decreased final angle of rotation θ_3 at time t_3 at the end of the east-west switch, to insure the secondary concentrated solar radiation 6 is directed at a decreased final angle 50 Ψ_3 toward the west receiver 7. FIG. 18F provides a summary combined illustration of the example daily counterclockwise rotations which can be used to improve the performance of a doubled secondary concentrator, with positions of the rotating doubled secondary concentrator over the day condensed into one figure.

[0200] Observe during the day up to the time of the east-west switch, since the secondary concentrator is tracking east to west toward the east receiver 7, both angle 50 Ψ as well as the counterclockwise angle θ of rotation increase, and thus rotation angle θ_0 is less than rotation angle θ_1 . Recall that the east-west switch can induce an abrupt change in angle 50 Ψ since prior to the east-west switch the east receiver 7 it is used to determine the angle 50 Ψ , while after the east-west switch the west receiver 7 is used to determine the angle 50 Ψ . Hence the rotational angle θ should also be correspondingly reset during the east-west switch and, depending on the number and configuration of the optical surfaces 38, 39 of the secondary concentrator, this east-west switch may provoke a considerable change in the rotational angle θ . Observe that during the day after the time of the east-west switch, since the secondary concentrator is tracking east to west away from the east receiver 7, both the angle 50 Ψ as well as the counterclockwise angle θ of rotation need to decrease, and so the rotation angle θ_3 is smaller than the rotation angle θ_2 . The exact relationship between the values of the rotation angle θ and the angle 50 Ψ over the day depend on the configuration of the optical surfaces 38, 39 of the secondary concentrator.

Tracking Apparatus 3: Rotational Tracking of a Doubled Reflective Secondary Concentrator

[0201] In some embodiments, Tracking Apparatus 3 uses a single cam for inducing rotation to compensate for the change in angle 50 Ψ during the secondary concentrator's east-west translational movement.

[0202] FIG. 19A illustrates an example of a Type 3 (rotating, non-elevating, double) secondary concentrator 168 used in Tracking Apparatus 3, with the cam disk 32 directly attached to the secondary concentrator 168 and cam guide 122 using a cam peg 121. The cam guide 122 initially slants gently upward, then will change its angle of slant abruptly down for the east-west switch, and the afterward slants gently downward. The cam peg 121 is located at the 11 AM (that is, upper left) position on the cam disk 32 in its initial position.

The west to east translational tracking then forces the cam disk 32 (and therefore the secondary concentrator 168) to rotate slowly counterclockwise.

[0203] For this cam system to correctly operate, this total rotation change should be less than a value Π , and therefore the two optical surfaces 38, 39 of the double secondary concentrator 168 is designed so that $\theta_2 - \theta_0 < \Pi$. Since $\theta_3 < \theta_0$, the total rotation deviation over the day can be bounded by $\theta_2 - \theta_0$.

[0204] The illustrations FIG. 19B-19F show the cam-based rotational Tracking Apparatus 3, with example illustrations at various distinct times throughout the day of the translational tracking of the non-rotating doubled secondary concentrator 168 as well as illustrations of the engaged cam guide 122 inducing counterclockwise rotation of the cam disk 32 and doubled secondary concentrator 168.

[0205] FIG. 19B illustrates Tracking Apparatus 3 at the start time t_0 of the daily tracking, with position of the engaged single cam guide 122 at the upper left position on the cam disk 32 resulting in a relatively small angle of rotation θ_0 of the doubled secondary concentrator 168. The gentle upward slant of the cam guide 122 at this period causes the cam disk 32 to rotate in a relatively slow counterclockwise direction.

[0206] FIG. 19C illustrates Tracking Apparatus 3 at time t_1 with an increased angle of rotation θ_1 of the doubled secondary concentrator 168. Recall that the east-west switch can induce an abrupt change in angle 50Ψ since prior to the east-west switch the angle 50Ψ can be determined using the position of the east receiver, and after the east-west switch the angle 50Ψ can be determined using the position of the west receiver. Hence the angle of rotation θ should also be correspondingly reset.

[0207] FIG. 19D illustrates Tracking Apparatus 3 at time t_2 (with change in rotation angle θ from at time t_1) resulting in the reset angle of rotation θ_2 of the doubled secondary concentrator 168. The gentle upward slant of the cam guide 122 at this period again causes the cam disk 32 to rotate in a relatively slow counterclockwise direction.

[0208] FIG. 19E illustrates the final position at time t_1 with the decreased final angle of rotation θ_3 of the doubled secondary concentrator.

[0209] FIG. 19F provides a summary combined illustration of the daily movement of the cam-based rotational Tracking Apparatus 3, with positions of the engaged single cam guide 122 and doubled secondary concentrator 168 over the day condensed into one figure. After the end of the solar day, the cam-based tracking movement can be reversed to allow the secondary concentrator 168 and cam guide 122 to be repositioned to the start of day position.

[0210] In some embodiments, each of the two optical surfaces 38, 39 of the double secondary concentrator 168 are rotated by the appropriate amount, so that the rotational angle θ_2 is substantially equivalent to the rotational angle θ_3 , and hence there is no need to induce a rotational change during the east-west switch.

Tracking Apparatus 4: Rotational Tracking of a Singleton Reflective Secondary Concentrator

[0211] In certain embodiments, Tracking Apparatus 4 uses a Type 4 (rotating, non-elevating, single) secondary concentrator 170 with one optical face 38. The secondary concentrator 170, as illustrated in FIGS. 20A-20G, includes a cam peg 131 and a cam guide 132. FIG. 20A provides details of the singleton secondary concentrator 170 with the single cam guide 132. The cam disk 32 can be directly attached to the

secondary concentrator 170, cam peg 131 and cam guide 132. The cam guide 132 initially slants gently upward, then slants steeply upward for the east-west switch, and again slants gently upward upon conclusion of the east-west switch. The cam peg 131 is located at the upper right position on the cam disk 32 in its initial position. The west to east translational tracking in conjunction with the cam guide 132 can be used to force the cam disk 32 (and therefore the secondary concentrator 170) counterclockwise at various rates during the day.

[0212] FIGS. 20B-20G illustrate Tracking Apparatus 4, with position of the engaged single cam guide 132 and secondary concentrator 170 at various angles of rotation at five example times throughout the day.

[0213] FIG. 20B illustrates the initial position at start time t_0 of the daily tracking, with the engaged single cam guide 132 at the upper left position on the cam disk 32 resulting in a relatively small angle of rotation θ_0 of the singleton secondary concentrator 170. The cam disk 32 then rotates slowly counterclockwise.

[0214] FIG. 20C illustrates the position at time t_1 of the engaged single cam guide 132 and singleton secondary concentrator 170 at increased angle of rotation θ_1 . The cam disk 32 then rotates relatively quickly counterclockwise for the east-west switch.

[0215] FIG. 20D illustrates the position at time t_m (in the middle of the east-west switch) with the optical face 38 of the singleton secondary concentrator 170 generally facing nearly upward.

[0216] FIG. 20E illustrates the position at time t_2 with the reset angle of rotation θ_2 . This one-cam rotational Tracking Apparatus 4 has the useful property that during the west-west switch, the solar radiation continues to be concentrated generally upward (rather than at any time downward, which would otherwise potentially damage the primary concentrator).

[0217] The cam disk 32 then rotates further slowly counterclockwise. FIG. 20F illustrates Tracking Apparatus 4 at the end time t_3 of the daily tracking, with position of the engaged single cam guide 132 and the singleton secondary concentrator 170 at increased final rotation angle θ_3 .

[0218] FIG. 20G gives a summary combined illustration of the daily movement of Tracking Apparatus 4, with the positions of the engaged single cam guide 132 and singleton secondary concentrator 170 at five distinct times over the day condensed into one figure. After the end of the solar day, the cam-based tracking movement can be reversed to allow the secondary concentrator 170 and cam guide 132 to be reset to the start of day position.

Tracking Apparatus 5—Translational Tracking of a Pair of Refractive Secondary Concentrators

[0219] In some embodiments, the Tracking Apparatus 1 makes use of west to east translational tracking of a Type 1 (non-rotating, non-elevating, double, operationally-reflective) secondary concentrator associated with each primary concentrator.

[0220] In certain embodiments, as illustrated in FIG. 21, Tracking Apparatus 5 includes a pair (termed eastern-facing-refractive and western-facing-refractive, respectively) of distinct, horizontally separated refractive secondary concentrators 172a and 172b. Both these eastern-facing-refractive and western-facing-refractive secondary concentrators 172a and 172b, for example, are associated with the same primary concentrator. They can be attached to the same two support

cables 30, and each attached so they are non-rotating and non-elevating. The eastern-facing-refractive secondary concentrator 172a can be attached to the support cables 30 to the east, and western-facing-refractive secondary concentrator 172b can be attached to the support cables 30 to the west, with sufficient separation so they do not obstruct their refracted radiation directed to the receivers.

[0221] Each of these refractive secondary concentrators 172a, 172b has a saw-tooth contoured operationally-refractive optical surface 38, 39 (e.g., as described in relation to FIG. 7J). The eastern-facing-refractive secondary concentrator 172a can be slanted downward from the east to the west, and can be designed so that it directs primary concentrated radiation, received from the east from the primary concentrator beneath, to the western receiver. The western-facing-refractive secondary concentrator 172b can be slanted downward from the west to the east, and can be designed so that it directs primary concentrated radiation, received from the west from the primary concentrator beneath, to the eastern receiver.

[0222] The receiver-directed focal line for the eastern-facing-refractive secondary concentrator 172a, for example, is a hypothetical line where radiation from the western receiver would be focused. The receiver-directed focal line for the western-facing-refractive secondary concentrator 172b, for example, is a hypothetical line where radiation from the eastern receiver would be focused.

[0223] The Tracking Apparatus 5 can make use of a schedule of daily west to east translational tracking similar to that described in relation to Tracking Apparatus 1 with regards to FIGS. 16A-D. The eastern-facing-refractive secondary concentrator 172a can provide the active optical surface 39 during the period of time from the start time t_0 of the daily tracking to the time t_1 of beginning an east-west switch. For example, the receiver-directed focal line of the eastern-facing-refractive secondary concentrator 172a can substantially coincide with the focal line of the primary concentrator, and its concentrated radiation can be directed to the west receiver. The east-west switch can be executed by rapid west to east translational tracking similar to that described in detail for Tracking Apparatus 1 (e.g., see FIGS. 16A-B). The western-facing-refractive secondary concentrator 172b can provide the active optical surface 38 during the time t_2 of completing an east-west switch to the end time t_3 . For example, the receiver-directed focal line of the western-facing-refractive secondary concentrator 172b can substantially coincide with the focal line of the primary concentrator, and its concentrated radiation can be directed to the east receiver. After the end of the daily tracking, the tracking of the secondary concentrators is reversed, so as to position them for the start time of the next day.

Tracking Apparatus 6: Translational Tracking of a Refractive and a Reflective Secondary Concentrator, with Only One Receiver

[0224] In some embodiments, Tracking Apparatus 6 directs all concentrated radiation to only one receiver. As shown in FIG. 22, Tracking Apparatus 6 can include a pair of distinct, horizontally separated secondary concentrators 174, termed an eastern-facing-reflective secondary concentrator 174a and a western-facing-refractive secondary concentrator 174b, respectively. Both the eastern-facing secondary concentrator 174a and the western-facing secondary concentrator 174b can be associated with the same primary concentrator. The

eastern-facing-reflective secondary concentrator 174a and a western-facing-refractive secondary concentrator 174b, in some implementations, are both attached to the same two support cables 30, and each can be attached in a non-rotating and non-elevating manner. The eastern-facing-reflective secondary concentrator 174a can be attached to the support cables 30 to the east and the western-facing-refractive secondary concentrator 174b can be attached to the support cables 30 to the west, with sufficient separation so they do not obstruct their refracted radiation directed to the receivers.

[0225] The eastern-facing-reflective secondary concentrator 174a can direct primary concentrated radiation, directed from the east from the primary concentrator beneath, to the eastern receiver. The optical surface 39 of the eastern-facing-reflective secondary concentrator 174a, in some examples, can be configured as either a concave contoured eastern-facing reflective optical surface or a saw-tooth contoured and operationally-reflective optical surface, as illustrated in relation to FIGS. 7H and 7I respectively. The optical surface 38 of the western-facing-refractive secondary concentrator 174b, for example, can be configured similar to the optical surface 38 described in relation to FIG. 7J. In some implementations, the optical surface 38 of the western-facing-refractive secondary concentrator 174b is slanted downward from the west to the east and designed so that it directs primary concentrated radiation, directed from the west from the primary concentrator beneath, to the eastern receiver.

[0226] The receiver-directed focal line for the eastern-facing-reflective secondary concentrator 174a, for example, is a hypothetical line where radiation from the eastern receiver would be focused. The receiver-directed focal line for the western-facing-refractive secondary concentrator 174b, for example, is a hypothetical line where radiation from the eastern receiver would be focused.

[0227] In some embodiments, the Tracking Apparatus 6 can make use of a schedule of daily west to east translational tracking similar to Tracking Apparatus 1, described in relation to FIGS. 16A-D. The eastern-facing-reflective secondary concentrator 174a, for example, can provide the active optical surface 39 during the period of time from the start time t_0 of the daily tracking to the time t_1 of beginning an east-west switch. For example, the receiver-directed focal line of the eastern-facing-reflective secondary concentrator 174a can substantially coincide with the focal line of the primary concentrator, and its concentrated radiation can be directed to the east receiver. The east-west switch can be executed by rapid west to east translational tracking similar to the east-west switch as described in relation to Tracking Apparatus 1 (e.g., see FIGS. 16B-C). The western-facing-refractive secondary concentrator 174b can provide the active optical surface 38 during the time t_2 of completing an east-west switch to the end time t_3 . For example, the receiver-directed focal line of the western-facing-refractive secondary concentrator 174b can coincide with the focal line of the primary concentrator, and its concentrated radiation can be directed to the east receiver. After the end of the daily tracking, in some implementations, the tracking of the secondary concentrators 174a, 174b can be reversed, so as to position the secondary concentrators 174a, 174b for the start time of the next day.

[0228] In other embodiments, a tracking apparatus similar to Tracking Apparatus 6 can be provided with a western-

facing-reflective secondary concentrator and an eastern-facing-refractive secondary concentrator.

Tracking Apparatus 7: Rotational Tracking of a Single Refractive Secondary Concentrator

[0229] In some embodiments, Tracking Apparatus 7 makes use of a singleton refractive secondary concentrator. Tracking Apparatus 7 includes a singleton reflective secondary concentrator similar to a Type 4 (e.g., rotating, non-elevating, singleton, operationally-reflective) secondary concentrator as described in relation to FIG. 7D, except the optical surface of the singleton refractive secondary concentrator. Of Tracking Apparatus 7 has a saw-tooth contour and is operationally-refractive (e.g., as described in relation to FIG. 7J).

[0230] The Tracking Apparatus 7, in some embodiments, makes use of a schedule of daily west to east translational tracking and cam-based rotational tracking similar to Tracking Apparatus 4, described in relation to FIGS. 20B-20G, except the opposite receivers can receive the concentrated solar radiation. The singleton reflective secondary concentrator, initially facing east, can provide the active optical surface during both the period of time from the start time t_0 of the daily tracking to the time t_1 of beginning an east-west switch. For example, the receiver-directed focal line of the singleton refractive secondary concentrator can substantially coincide with the focal line of the primary concentrator, and its concentrated radiation can be directed to the west receiver. The east-west switch can be executed by rapid cam-based rotational tracking as described in detail for Tracking Apparatus 4 (e.g., see FIGS. 20C-E). The same singleton reflective secondary concentrator, now facing west, can provide the active optical surface during the time t_2 of completing an east-west switch to the end time t_3 . For example, the receiver-directed focal line of the singleton reflective secondary concentrator can substantially coincide with the focal line of the primary concentrator, and its concentrated radiation can be directed to the east receiver. In some implementations, after the end of the daily tracking, the tracking of the singleton reflective secondary concentrator can be reversed, so as to position it for the start time of the next day.

[0231] In other embodiments, the single cam systems can include a second inner cam to allow for more rapid rotation during the east-west switch. To enable this functionality, for example, a further cam disk and cam guide can be added, with a cam peg closer to the axis of rotation, is the further cam disk being only engaged during the east-west switch while the other cam is disengaged.

[0232] Recall that the north-south position of the solar radiation concentrated on the receiver changes through the year. In some embodiments, as shown in FIG. 23A, each receiver is immobile but the secondary concentrators 5 make a rotational swivel (e.g., see focal line 42 in relation to secondary concentrator 5) slightly away from the north-south axis to compensate for a seasonal displacement of solar irradiation. For example, the rotational swivel can compensate for the changing slant of the concentrated solar radiation over the year, directing the secondary concentrated solar radiation 6 to the appropriate immobile receiver.

[0233] In some embodiments, as shown in FIG. 23B, the receiver 7 moves on a north-south axis to slowly track over the year by shifting horizontally 43 on the north-south axis so as to compensate for the changing slant of the concentrated solar radiation over the year.

[0234] FIG. 23C illustrates an example of the receiver 7 with a vertically stacked array of horizontal evacuated receiver tubes, arranged in a linear pattern, used as absorbers of the concentrated solar radiation. The absorbing region of the receiver 7 can be positioned as an array of receiver tubes, each with center axis running horizontally north-south. In another embodiment, shown in relation to FIG. 23D, multiple receiver tubes can be arranged in a zigzag pattern of displaced vertical columns. In this arrangement, the center axis of each receiver tube and the nearest neighboring receiver tube can be vertically displaced by a fixed distance and also displaced in the east-west direction by a fixed distance. For example, if the receiver tubes have outside diameter d , the receiver tubes can be arranged in a zig-zag displaced vertical column so the center axis of consecutive receiver tubes are vertically displaced by $d \sqrt{2}$ and also displaced in the east-west direction by $d \sqrt{2}$, so the distance between each respective receiver tube axis is $2d$.

[0235] The effect of this particular arrangement of receiver tubes is first to partly obscure a significant portion of the surface of every second tube that is not normal to the incoming concentrated solar radiation and second to increase the proportion of the surface of the receiver tubes that receive incoming concentrated solar radiation at an angle near normal to the surface of each respective tube. Since the transmittance of the outer glass surface of each tube is highest for solar radiation that is normal to the surface, this positioning of the receiver tubes can improve the overall transmittance of concentrated solar radiation directed to the absorbing region of the receiver.

Storage of Concentrated Thermal Solar Energy

[0236] In certain embodiments, providing apparatus for energy storage increases the total cost of the manufacture of the overall system, but potentially further increases the cost efficiency, allowing the solar conversion process to occur for a period beyond the solar energy collection period. Since the one or more receivers are centralized, the heat exchanger and energy storage apparatus can also be centrally located near or within the receivers, in some embodiments, to insure rapid and efficient heat transfer. When the receiver absorbing materials cool, for example after completion of the solar day or during a day with reduced direct solar radiation, the stored heat is released.

[0237] In certain embodiments, the solar energy system includes an apparatus for bulk thermal storage of the solar energy concentrated at the receivers. In certain embodiments, the apparatus for bulk thermal storage includes the bulk heat storage materials, storage containers for the bulk material, as well as heat exchangers that provide heat transfer to and from the bulk thermal storage material, as well as insulation used to reduce heat loss. The materials used in this alternative embodiment for bulk thermal storage can include, but are not limited to, liquid sulfur, molten salt, mineral oils, and concrete. Concrete, for example, is likely the lowest cost of these bulk thermal storage materials. While conventional concrete generally consists of a mixture of an aggregate, portland cement, water, and admixtures, in certain embodiments the bulk thermal storage material consists of high-temperature concrete, for example, the MEYCO Fireshield 1350©, available from BASF SE of Ludwigshafen, Germany. The bulk thermal storage material, in this example, can be made by replacing the usual aggregate with an alternative material.

[0238] In some embodiments, the solar energy system includes an apparatus for phase-change storage of the solar energy concentrated by the centralized receivers. The heat exchangers and storage containers for the phase-change materials, for example, can be located within or just in back of the receivers and insulation can be used to reduce heat loss. The substances used for bulk thermal storage, for example, can include various salts which form eutectics with other salts and other materials which store and release heat by melting and solidifying, respectively. Examples of these phase-change materials include NaCl, NaNO₃, KNO₃, as well as the combination of ZnCl₂ and KCl, and the combination of MgCl and NaCl.

[0239] In certain embodiments, the solar concentrator system includes an apparatus for chemical energy storage of the concentrated solar energy at the receivers. Typically, the chemicals provide that energy storage react in the presence of heat and catalysis. The reaction absorbs heat, and various chemical products are stored. After the solar day, the stored heat can be released by a reverse reaction.

[0240] An example apparatus for storage of the concentrated solar energy is illustrated in FIGS. 24A (illustrating heat storage) and 24B (illustrating heat release), where a metallic hydride (such as magnesium hydride (MgH₂) powder), for example, can be used to store energy by dissociation to the base metal and hydrogen gas. The apparatus includes a chamber 142 that uses heat energy to produce pressurized gas and a gas storage chamber 144. A heat energy flow 141, provided from the receiver, is passed to the chamber 142. The chamber 142, in turn, passes a pressurized gas flow 143 to the gas storage chamber 144. The receiver, for example, can contain one or more reaction chambers such as the reaction chamber 142. The reaction chamber 142, for example, can be constructed as an array of horizontal pipes, each partly filled with a metallic hydride powder suspended in a solvent such as toluene along with catalysts for the reaction. The reaction chamber 142 is connected to the large storage chamber 144 where the resulting dissociated H₂ can be stored at the resulting dissociation pressure.

[0241] As further illustrated in FIG. 24B, when the base metal cools after the solar day (or during a day with reduced direct solar radiation), the hydrogen can flow back from the storage chamber 144 to the base metal in the reaction chamber 142 where the hydrogen reacts to reform a metallic hydride, releasing the stored thermal energy for applications after the solar day.

[0242] In certain embodiments, the thermal storage is partitioned into a series of blocks of thermal storage, the blocks providing thermal storage in the form of bulk heat storage, chemical heat storage, or phase-change energy storage. The number of blocks of thermal storage currently used, in some embodiments, can be dynamically varied in accordance to the total amount of concentrated solar energy needed to be stored. There can be means, for example, for heat transport between certain of these blocks, as well as means for heat transport from the solar collecting system to these blocks and also means for heat transport from certain of these blocks to the system using the concentrated solar energy. In the initial case of no heat being currently stored, for example, only one block of heat storage may be active. Additional blocks can be activated when needed for additional heat storage, and blocks can be deactivated when no longer needed for additional heat storage.

[0243] In certain embodiments of this dynamic thermal storage system, the blocks are configured in one or more linear arrays, wherein only a consecutive subsequence of blocks is activated for energy storage at any time. There can be means for heat transport between each consecutive pair of blocks, as well as heat transport from the solar collecting system to the first block of each array of blocks as well as means for heat transport from the first block of each array to the system that uses the concentrated solar energy. In the initial case of no heat being currently stored, for example, only the first block of each array of heat storage blocks is actively used for heat storage. When needed for additional heat storage, the unique unactivated(?) block neighboring the currently activated sequence of blocks can be activated by transporting heat to it. One or more blocks at the end of this activated sequence, for example, may be deactivated by no longer transporting heat to them when they are no longer needed for heat storage.

Electrical Power Generation

[0244] In alternative embodiments, the solar concentrator system includes a power-block that makes use of photovoltaic panels that convert the concentrated solar energy to produce electrical energy.

[0245] In some embodiments, as shown in FIG. 25A, the solar energy system includes a power-block that makes use of heated steam to drive a gas turbine. In this embodiment, steam pipes 176 run through the receiver 7, absorbing thermal energy. The steam pipes 176 lead to a gas turbine electrical power generator 145 which generates electricity from the flow of pressurized gas through its turbine blades. Here volume expansion, due to the use of the concentrated solar energy to boil water into a large volume of steam, can be used to convert the thermal energy into kinetic energy to drive the gas turbine electrical power generator 145. After driving through the gas turbine electrical power generator 145, the steam enters a return gas storage chamber 147 which, for this application, may optionally contain a cooling tower unit allowing the steam to condense back into water. The steam or water is returned back from the return gas storage chamber 147 to the steam pipes 176 of the receiver 7 and/or, optionally, a heat storage unit (not illustrated). The rate of return flow of the steam or water from the return gas storage chamber 147 to the receiver 7 or heat storage unit, for example, can be controlled by a back-flow control valve 148.

[0246] In some embodiments, the solar energy system includes a power-block that makes use of pressurized hydrogen gas, for example obtained by heating a metallic hydride, to drive a gas turbine. FIG. 25B can be alternatively used to illustrate the flow of energy and gas through the power-block. In brief, heat energy 141 provides for the metallic hydride's heat-induced disassociation into the base metal and pressurized hydrogen gas, absorbing thermal energy. The hydrogen gas feeds through the gas turbine electrical generator 145 and is collected at the return storage chamber 147. Finally, the gas flows back to the receiver 7, with the rate of return flow controlled by the back-flow control valve 148. The steps of this energy cycle are further detailed below:

[0247] Within the receiver 7 is a reaction chamber consisting of an array of horizontal steam pipes 176, filled, for example, with a metallic hydride as well as catalysts. The concentrated solar heating (to disassociation temperature) of the metallic hydride (such as magnesium hydride) in the

reaction chamber at the receiver 7 results in two reaction products: the base metal product and hydrogen gas H_2 at the dissociation pressure.

[0248] The volume expansion, from the release of a large volume of hydrogen gas H_2 product, can be used to convert the thermal energy into kinetic energy to drive the gas turbine of the gas turbine electrical power generator 145. The reaction chamber can be connected by one or more pipes to the gas turbine electrical power generator 145. Such turbines, for example, can have up to 42% efficiency depending on size.

[0249] After driving through the gas turbine electrical power generator 145, the hydrogen enters the return storage chamber 147 which also, for example, has a pipe (used after the solar energy generation has ended for the day) back to the metallic hydride reaction chamber 142.

[0250] The use of a metallic hydride/hydrogen turbine for conversion from heat energy to electrical power can provide improved efficiency over a steam turbine system, since the temperature differential between the cooled state and the heated state required for gaseous dissociation can be considerably larger in the metallic hydride/hydrogen turbine energy conversion system than a steam turbine system.

[0251] In some embodiments, the power block closes the back-flow control 148 during the period of the solar day when heat energy is generated. Then, after the solar day, when the base metal of the metallic hydride in the reaction chamber 142 has cooled, the back-flow control valve 148 can be opened to allow the hydrogen to flow back to the reaction chamber 142.

[0252] In some embodiments, an additional gas storage chamber 144 for storage of energy is added to the power block, as illustrated in FIG. 25B. The heat energy 141 provides for the metallic hydride's heat-induced disassociation into the base metal and pressurized hydrogen gas, absorbing thermal energy. Some of the resulting hydrogen gas flows to the temporary storage provided by the additional gas storage chamber 144, and the remainder of the hydrogen gas feeds through the gas turbine electrical generator 145, and is collected at the return storage chamber 147. Finally, the gas flows back to the reaction chamber 142. After the solar day, the hydrogen gas stored in the temporary storage chamber 144 can flow back to the reaction chamber 142, which reacts with the base metal to form again metallic hydride, liberating heat which creates an increased gas pressure to further drive the gas turbine electrical generator 145.

[0253] Concentrated solar thermal-electrical plants can make use of solar radiation (e.g., primarily in the infrared (IR) range) to generate electricity, where as solar photovoltaic (PV) plants make use of solar radiation primarily in the UV and VIS ranges to generate electricity.

[0254] In certain embodiments, the solar energy system includes an apparatus for separation of concentrated solar radiation in the IR range from the solar radiation in UV and VIS ranges, and apparatus for thermal-electrical generation for harvesting the solar energy in the IR range, as well photovoltaic apparatus for harvesting the solar energy in the UV and VIS ranges.

[0255] Through the use of refractive and/or reflective surfaces with optical coatings, solar radiation in the IR range can be separated from the solar radiation in UV and VIS ranges. In some embodiments, the separation of the IR range from the UV and VIS ranges is achieved at the primary concentrators. In other embodiments, the separation of the IR range from the UV and VIS ranges is achieved at the secondary concentra-

tors. In alternative embodiments, the receivers separate solar radiation in the IR range from solar radiation in the UV and VIS ranges.

[0256] In the case where the separation is done at the receivers, each of at least two (e.g., east, west) receivers can be portioned into a pair of subreceivers A and B, one for absorbing primarily in the IR range, and the other for absorbing primarily in the UV and VIS ranges.

[0257] For example, FIG. 26 illustrates the concentrated solar radiation from the secondary concentrators directed to the east receiver 7, which is partitioned into subreceiver A 151, and subreceiver B 152. In an example configuration, subreceiver A 151 has an optical surface that reflects incoming radiation primarily in the IR, but absorbs incoming radiation primarily in the UV and VIS ranges, while subreceiver B 152 absorbs the radiation (e.g., primarily in the UV and VIS range) reflected from subreceiver A 151. Alternatively, subreceiver A 151 can be provided with an optical surface that reflects incoming radiation primarily in the UV and VIS ranges but absorbs incoming radiation primarily in the IR ranges. In this example, subreceiver B 152 can absorb the (e.g., primarily IR) radiation reflected from subreceiver A 151.

[0258] In some embodiments, the solar energy system includes systems for generation of electrical energy as well as a system for distribution of the remaining and/or waste thermal energy for other productive use. The further productive use of this thermal energy can include, in some examples, smelting, the heating of buildings, the enhancement of chemical reactions (e.g., heating water to enhance the production of hydrogen by electrolysis), and further generation of electrical energy by thermal-cycles with lower temperature differentials.

[0259] In certain embodiments, the solar energy system includes systems for generation of electrical energy where a portion of the electricity can be used for generation of hydrogen energy by electrolysis. The remaining and/or waste thermal energy, for example, can be used in part for heating water to enhance this production of hydrogen by electrolysis.

[0260] A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

What is claimed is:

1. A solar concentrator system comprising:

one or more stationary primary concentrators positioned to receive solar irradiation, each of the one or more stationary primary concentrators including a generally curved optical surface capable of reflecting solar irradiation as primary concentrated solar radiation, the primary concentrated solar radiation substantially reflected to a position proximate a first focal line;

one or more articulating secondary concentrators, each articulating secondary concentrator positioned generally above a respective stationary primary concentrator such that a first optical surface of each articulating secondary concentrator is positioned proximate the first focal line, the first optical surface of each articulating secondary concentrator receiving primary concentrated solar radiation reflected by a respective stationary primary concentrator and reflecting the primary concentrated solar radiation as secondary concentrated solar radiation;

one or more passive centralized receivers configured to substantially absorb energy received as secondary concentrated solar radiation reflected by the one or more articulating secondary concentrators, wherein the one or more articulating secondary concentrators reflect the secondary concentrated solar radiation in a substantially lateral direction towards the one or more passive centralized receivers; and

a tracking system configured to determine a drift in the first focal line and to adjust the one or more articulating secondary concentrators to correct for the drift in the first focal line.

2. The system of claim **1**, further comprising:

a tensile structure from which the one or more articulating secondary concentrators are suspended; and

a support structure supporting the tensile structure, the support structure including a combination of one or more substructures, each substructure having at least one of compressive, flexing, and tensile properties.

3. The system of claim **2**, wherein the tensile structure includes one or more support cables.

4. The system of claim **2**, further comprising an open loop control system configured to compensate for dynamic effects using dynamic corrections to at least one of the one or more articulating secondary concentrators and the tensile structure, wherein the open loop control system makes dynamic corrections in at least one of position, orientation, and tension.

5. The system of claim **1**, wherein at least one of the one or more articulating secondary concentrators and the one or more stationary primary concentrators include an optical surface with a saw-tooth contour.

6. The system of claim **1**, wherein at least one of the one or more articulating secondary concentrators and the one or more stationary primary concentrators include an optical surface with refractive properties.

7. The system of claim **1**, wherein the one or more passive centralized receivers include a first passive centralized receiver and a second passive centralized receiver,

the first passive centralized receiver being positioned at a first end of the one or more stationary primary concentrators, and

the second passive centralized receiver being positioned at a second end of the one or more stationary primary concentrators, the second end being opposite the first end.

8. The system of claim **7**, wherein

the one or more articulating secondary concentrators each include a second optical surface; and

adjusting the articulating secondary concentrators to correct for the drift in the first focal line by the tracking system includes:

adjusting each of the one or more articulating secondary concentrators to orient the first optical surface to reflect secondary concentrated solar radiation towards the first passive centralized receiver during a first part of a solar day, and

adjusting each of the one or more articulating secondary concentrators to orient the second optical surface to reflect secondary concentrated solar radiation towards the second passive centralized receiver during a second part of the solar day.

9. The system of claim **1**, wherein the tracking system is further configured to determine a seasonal displacement of the first focal line and to adjust the one or more articulating

secondary concentrators to correct for the seasonal displacement in the first focal line, wherein seasonable displacement adjustments include at least one of:

adjusting each of the one or more articulating secondary concentrators to reorient the first optical surface to reflect secondary concentrated solar radiation towards a respective passive centralized receiver, and

adjusting each of the one or more passive centralized receivers to reorient towards a direction of secondary concentrated solar radiation being reflected from a respective articulating secondary concentrator.

10. The system of claim **9**, wherein

the tracking system is further configured to activate orientation movement to the one or more articulating secondary concentrators for adjusting each of the one or more articulating secondary concentrators to reorient the first optical surface, and

the orientation movement includes at least one of rotation and vertical displacement.

11. The system of claim **1**, wherein the one or more articulating secondary concentrators include means for protection from inclement weather.

12. The system of claim **1**, wherein the one or more passive centralized receivers are positioned at a substantially higher elevation than the one or more articulating secondary concentrators.

13. The system of claim **1**, wherein the one or more passive centralized receivers are partitioned into multiple sub-receivers, each sub-receiver including means to receive a portion of the secondary concentrated solar radiation having a frequency in a distinct frequency spectrum amplitude.

14. The system of claim **1**, wherein the one or more articulating secondary concentrators are positioned to be approximately uniform in height above the one or more stationary primary concentrators.

15. A method for directing primary concentrated solar radiation in a solar concentrator system, the method comprising:

determining, at a tracking system, a drift in a first focal line, the first focal line being a position towards which primary concentrated solar radiation is reflected by each of one or more stationary primary concentrators,

the one or more stationary primary concentrators being positioned to receive solar irradiation,

each of the one or more stationary primary concentrators including a generally curved optical surface capable of reflecting solar irradiation as primary concentrated solar radiation; and

adjusting, at the tracking system, one or more articulating secondary concentrators to correct for the drift in the first focal line,

each of the one or more articulating secondary concentrators being positioned generally above a respective stationary primary concentrator such that a first optical surface of each of the one or more articulating secondary concentrators substantially coincides with the first focal line,

the first optical surface of each of the one or more articulating secondary concentrators receiving primary concentrated solar radiation reflected by a respective stationary primary concentrator and reflecting the primary concentrated solar radiation as secondary concentrated solar radiation, wherein

adjustments enable the one or more articulating secondary concentrators to reflect the primary concentrated solar radiation received from the one or more stationary primary concentrators as secondary concentrated solar radiation in a substantially lateral direction towards one or more passive centralized receivers, the one or more passive centralized receivers being configured to substantially absorb energy received as secondary concentrated solar radiation.

16. The method of claim **15**, wherein the one or more articulating secondary concentrators are suspended from a tensile structure, the tensile structure being supported by a support structure including a combination of one or more substructures, each substructure having at least one of compressive, flexing, and tensile properties, the method further comprising:

compensating, at an open loop control system, for dynamic effects using dynamic corrections to at least one of the one or more articulating secondary concentrators and the tensile structure, wherein the open loop control system makes dynamic corrections in at least one of position, orientation, and tension.

17. The method of claim **15**, wherein

the one or more passive centralized receivers include a first passive centralized receiver and a second passive centralized receiver;

the first passive centralized receiver being positioned at a first end of the primary concentrators, and

the second passive centralized receiver being positioned at a second end of the primary concentrators, the second end being opposite the first end; and

the one or more articulating secondary concentrators each include a second optical surface, wherein the method further comprises:

tracking, at the tracking system, to adjust to seasonal displacement of solar irradiation, wherein seasonable displacement adjustments include at least one of:

adjusting each of the one or more articulating secondary concentrators to reorient towards a respective passive centralized receiver, and

adjusting each of the one or more passive centralized receivers to reorient towards a respective articulating secondary concentrator.

18. The method of claim **15**, further comprising:

determining, at the tracking system, a seasonal displacement of the first focal line; and

adjusting the one or more articulating secondary concentrators to correct for the seasonal displacement in the first focal line, wherein seasonable displacement adjustments include at least one of:

adjusting each of the one or more articulating secondary concentrators to reorient the first optical surface to reflect secondary concentrated solar radiation towards a respective passive centralized receiver, and
adjusting each of the one or more passive centralized receivers to reorient towards a direction of secondary concentrated solar radiation being reflected from a respective articulating secondary concentrator.

19. The method of claim **18**, wherein adjusting each of the one or more articulating secondary concentrators to reorient the first optical surface includes activating orientation movement to the one or more articulating secondary concentrators, wherein the orientation movement includes at least one of rotation and vertical displacement.

20. The method of claim **15**, wherein

the one or more articulating secondary concentrators are positioned in approximately uniform orientation with respect to a first axis, and

adjusting the one or more articulating secondary concentrators to correct for the drift in the first focal line includes tracking a translational movement of the one or more articulating secondary concentrators along approximately the first axis.

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