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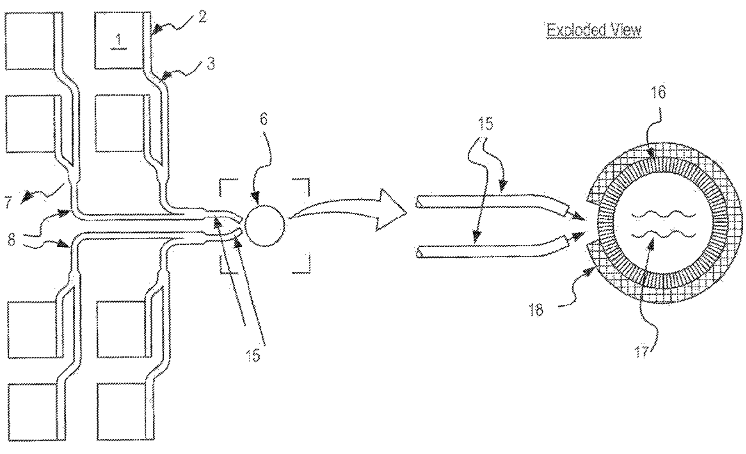

FIG. 5

(57) Abstract: A device for collection, concentrating and storing solar energy comprises an optical concentrator in operative connection with & transmission means which is also operatively connected to an energy recovery device, Concentrated solar energy is transmitted from the optical concentrator to the energy recovery device where it is stored until it Is deployed as an energy source for generating electricity.

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RADIATION COLLECTION UTILIZING TOTAL INTERNAL REFLECTION AND OTHER TECHNIQUES FOR THE PURPOSE OF DISPATCHABLE ELECTRICITY GENERATION AND OTHER USES

STATEMENT AS TO RIGHTS TO INVENTIONS MADE UNDER FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0001] N/A.

FIELD OF THE INVENTION

[0002] The present invention relates generally to solar power generation systems. In particular, the invention relates to a solar power tower generation system with high operating temperatures.

BACKGROUND OF THE INVENTION

[0003] There is a continuing demand for clean renewable energy sources, such as solar power. An exemplary solution to this demand resides in the art of solar power towers. The global electricity generation portfolio (that is, the mix of types of generation that make up the overall electricity generation system) has increasingly incorporated electricity generated from solar energy. This has had numerous benefits for the electric power industry, the environment, electricity consumers, and society as a whole.

[0004] Solar-generated electricity typically suffers from certain defects. The first typical defect of solar-generated electricity is that it is only generated when the sun is shining on the generating equipment. This has deleterious effects on the electric grid, when compared respectively to "base load" generation resources and "dispatchable" generation resources. Typically, solar-generated electricity provides no electricity when the sun is below the horizon and no or less electricity when the sun obscured by clouds. Thus, typical solar-generated electricity is inferior to "base load" generating resources, such as coal, nuclear, and geothermal, which reliably provide electricity around the clock, and "dispatchable" resources, such as hydroelectric and gas-fired, which provide varying capacities in response to fluctuating load.

[0005] This defect is becoming increasingly problematic as the penetration of solar-generated electricity into the grids of certain regions increases. For example, California is projected to achieve 33% penetration of renewable energy in its grid by 2020, creating grid management problems which will result from the large amount of solar-generated electricity in the state's generation portfolio in 2020.

[0006] Prior devices intended to address this defect are solar power towers (**FIG. 6**). Solar power towers generate electric power from sunlight by focusing concentrated solar radiation on a tower-mounted receiver. Solar electric generating plant combined with thermal storage, whereby numerous mirrors are placed in a field, each equipped with two-axis tracking devices which enable all the mirrors to concentrate solar radiation on a heat exchanger located in a tower high above the field of mirrors. By achieving high levels of concentration of the radiation, high temperatures can be achieved in the heat exchanger. A medium suitable for storing heat in a high ratio of energy stored to volume, such as salt, can be circulated through the heat exchanger, then stored, typically in molten form, and later used to generate electricity, for example by producing steam to drive a steam turbine. Typically, this enables the solar generating plant to perform as a base load resource. It also enables the solar generating plant to perform as a peaking resource.

[0007] As shown in **FIG. 6**, the alignment system includes a solar power tower **110** with a focal area **112** and an off-focal area location **120** that is substantially close to the focal area **112** of the solar power tower **110**, a plurality of heliostats **130** with a reflective mirror **132** and a sun tracking mechanism **134** that moves and aligns the reflective mirror to reflect sunlight towards the focal area **112** of the solar power tower **110**.

[0008] The power tower design suffers from defects of technical complexity and high cost. The technical complexity and high cost arise from the following, among other factors. For example, each mirror must be precisely parabolic, in order to aim the reflected sunlight at a small heat exchanger a significant distance away. Because of the substantial distance between the mirrors and the heat exchanger, small errors in the parabolic shape of the mirror will result the reflected sunlight not being concentrated on the heat exchanger. This requires relatively exacting and expensive fabrication techniques and quality control. Each mirror must be highly reflective. This requires the use of expensive materials, such as silver, coating the reflective surface. Each mirror must be kept very clean and free of dust. This requires frequent maintenance. The mirrors must be highly accurate in reflecting the solar radiation, hitting a small target (the heat exchanger) at a large distance away. Because of the substantial distance between the mirrors and the heat exchanger, small aiming errors will result the reflected sunlight missing the heat exchanger and even harming nearby activities.

This low-tolerance aiming requires high-precision, and consequently high cost, tracking equipment. It also requires almost constant adjustment of the mirror's orientation, making it effectively necessary that each mirror have two dedicated motors, one each for azimuth and altitude. The heat exchanger must be mounted high on a tower, in order enable a large field of mirrors to "see" the heat exchanger. This requires the capital cost of the tower and the piping to bring the storage medium to the location of the generating equipment. It also requires maintenance personnel to mount the tower in order to perform maintenance activities. Each mirror must have its own algorithm for aiming, since the reflective angle connecting each mirror to the heat exchanger is unique. Moreover, because the aiming of the mirrors must be very precise, the mounting of the mirrors must be highly resistant to wind load, which will affect the shape and aim of the mirrors. This means that each mirror must be structurally robust enough to resist deflection under load, increasing its weight and cost, and the mounting of each mirror must secure the mirror precisely in position, increasing the weight and cost of the mounting equipment.

[0009] A second typical defect of solar generating technologies is capital cost. In particular, photovoltaic generation, the most common form of solar-generated electricity is expensive. A prior device that addresses this defect uses the principle of total internal reflection (TIR) to capture solar radiation which is incident to the surface of a transparent medium such as an acrylic panel and redirect it through the transparent medium toward one edge or a radial concentration region of the medium, where a small photovoltaic element receives the concentrated radiation. Typically, radiation passes approximately perpendicularly through the surface of a transparent panel and encounters a series of planar boundaries of the medium at angles of incidence within the numerical aperture of the material, that is, at angles less than that at which TIR occurs. This results in the directing of 100% of the radiation into a "wave guide", through which it can pass to an edge or to the center of the medium. A photovoltaic element is typically positioned at that downstream edge or center of the medium. The cost of the transparent medium is typically lower than the cost of the photovoltaic element, so the overall cost per unit of captured radiation is reduced.

[0010] Solar power tower systems typically include a "cold" storage tank, a solar receiver, heliostats, a "hot" storage tank, and an energy conversion system, such as a steam generator or turbine/generator set. In operation, a heat storage fluid is pumped from the cold storage tank to the solar receiver. The heat storage fluid can be any medium that has the capability to transfer heat and thermally maintain the heat in the medium, such as water, liquid metal, or molten salt.

[0011] Because the solar tower power generation plants rely so heavily on the concentration of solar energy, the efficiency of a solar tower power generation plant is heavily affected if the heliostats are inaccurate at tracking the sun and consequently are misaligned away from the focal area of the solar power tower. Heliostats typically track the sun in an open-loop manner, where the known positions of the sun are programmed into each heliostat and the mirror is moved according to the known positions. However, due to inaccuracies that may exist in the known positions of the sun and/or the movements of the heliostat mechanism, the actual orientation of the reflective mirror of the heliostat may not be at the desired location and the reflected sunlight may not be aligned correctly towards the focal area of the solar power tower, which decreases efficiency. According to a report published by Sandia National Laboratories, a reduction in sun tracking errors from just two to one milliradian may reduce the cost of a solar tower power generation plant as much as 5%.

[0012] Closed loop systems that track the actual reflection direction of the heliostat and then correct misalignment have been proposed, but are very costly to implement. Examples of such systems are disclosed in U.S. Pat. No. 7,207,327 and U.S. Patent Application Number 2009/0249787 that utilize image recognition techniques located at each heliostat. According to the report published by Sandia National Laboratories, the cost of heliostats constitutes about 60% of a solar tower power generation plant. The cost of implementing a reflection direction detection system for each individual heliostat will increase the overall cost of the solar tower power generation plant at least proportionally to the number of heliostats in the heliostat field, and with such high numbers of heliostats in each heliostat field, this may substantially increase the cost of the solar tower power generation plant. Cost of solar tower power generation plants is also a significant barrier to wider implementation of solar tower power generation plants.

[0013] Thus, there is a need in the solar power field to create an improved means of collecting, concentrating, storing and deploying solar energy free from the shortcomings of solar power towers incorporating heliostat and fields of such heliostats. Surprisingly, the present invention provides improved devices, systems and methods.

SUMMARY OF THE INVENTION

[0014] In various embodiments, the invention provides an optical concentrator that collects and concentrates solar energy. The optical concentrator is operatively linked to a transmission means configured to transmit radiation from the concentrator to a storage device to which the transmission device is also operatively linked.

[0015] In an exemplary embodiment, the optical concentrator is a device configured from a material capable of total internal reflection. The concentrator includes a waveguide, which concentrates the incident solar radiation and directs the concentrated solar radiation to a transmission device, which in an exemplary embodiment is a fiber optic cable. The transmission means directs the concentrated energy to a storage device, which in an exemplary embodiment is a vessel holding a heat storage means, e.g., a salt.

[0016] In an exemplary embodiment, the optical concentrator includes a first collection region that collects incident solar radiation and transmits the collected radiation to a second collection region where the transmitted radiation is concentrated before being directed to the transmission means. See, **FIG.1A** and **FIG. 1B**.

[0017] Thus, in operation, the optical concentrator collects incident solar radiation, concentrates it and directs it to the transmission means. The transmission means transmits the concentrated solar radiation to a storage device.

[0018] In various embodiments, the invention provides a system for collecting, concentrating and storing solar energy. In an exemplary embodiment, the system includes a plurality of optical concentrators linked in parallel and/or in series and operatively linked to an energy recovery device. In an exemplary embodiment, the members of the plurality of solar concentrators are linked via connections between their transmission means.

[0019] In various embodiments, there is also provided a method for collecting, concentrating and storing solar energy. In an exemplary embodiment, the method includes: (a) collecting incident solar radiation in an optical concentrator configured to concentrate the solar energy to a beam focused for transmission through a transmission means into an energy recovery device; and (b) transmitting the beam through the transmission means to the energy recovery device, transferring energy stored in the beam to the energy recovery device, thereby storing the energy. In an exemplary embodiment, the optical concentrator and the energy recovery device are operatively linked through the transmission means.

[0020] Other embodiments, objects and advantages of the current invention are apparent from the detailed description that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] **FIG. 1A** and **FIG. 1B** show respectively a plan view and an isometric view of an optical concentrator of use in the invention, including primary and secondary collectors and fiber optic cable for energy output. Also illustrated is the orientation of the axes of the concentrator and the location where section A is cut. The drawings illustrate a configuration of the first wave guide as a panel with orthogonal axes of redirection. The principles apply equally well to a panel with radial axes of redirection.

[0022] **FIG. 2** shows two versions of Section A through the optical concentrator of **FIG. 1**. The sections show the detail of the wave guide design in the primary collector but no detail in the secondary collector. **FIG. 2A** shows the path of light radiation during primary collection. Radiation R1 (the incoming radiation from the sun) is parallel to axis Z and perpendicular to axes X and Y. Radiation R1 is redirected by passage (reflection) through multiple aperatures **20**. Radiation R2 (the radiation after primary collection, exiting the primary collector, and entering the secondary collector) is perpendicular to axis X and within the numerical aperture with respect to axis Y. ("Numerical aperture" with respect to fiber optics describes the range of angles within which light that is incident on the fiber will be transmitted along it.). **FIG. 2B** shows an exemplary waveguide structure in the first collection region **1** with a plurality of aperatures **20**.

[0023] **FIG. 3A** and **FIG. 3B** show a plan view of the optical concentrator with the detail of the wave guide design in the secondary collector but no detail in the primary collector. **FIG. 3A** shows a plurality of aperatures **21**, and the transmission means **3**. In an exemplary embodiment, the transmission means includes a taper **5** allowing it to be attached to a fiber optic cable **4**. **FIG. 3B** shows the path of light radiation during secondary collection. Radiation R2 (the radiation entering the secondary collector) is perpendicular to axis X and within the numerical aperture with respect to axis Y. Radiation R3 (the radiation after secondary collection, exiting the secondary collector, and entering the fiber optic cable for output from the panel) is not perpendicular or parallel to any axis but is and within the numerical aperture with respect to axis X.

[0024] FIG. 4 shows multiple rows, each of multiple optical concentrators, illustrating a manner in which the fiber optic output cables may be combined, while keeping the radiation flow within the numerical aperture and tapering the cables within the limits described above.

[0025] FIG. 5 shows multiple optical concentrators, illustrating a manner in which multiple fiber optic cables, each carrying radiation from multiple panels, may be directed at a small area of the energry recovery device, e.g., a heat exchanger. The delivery of the fiber optic cables to a close proximity of the heat exchanger allows a tightly focused concentration of radiation on a small surface area of the heat exchanger.

[0026] FIG. 6 shows an exemplary conventional power tower.

DETAILED DESCRIPTION OF THE INVENTION

I. Introduction

[0027] Over the last five decades or so, the global electricity generation portfolio (that is, the mix of types of generation that make up the overall electricity generation system) has increasingly incorporated electricity generated from solar energy. This has had numerous benefits for the electric power industry, the environment, electricity consumers, and society as a whole.

[0028] However, solar-generated electricity typically suffers from certain defects. The first typical defect of solar-generated electricity is that it is only generated when the sun is shining on the generating equipment. This has deleterious effects on the electric grid, when compared respectively to "base load" generation resources and "dispatchable" generation resources. Typically, solar-generated electricity provides no electricity when the sun is below the horizon and no or less electricity when the sun obscured by clouds. Thus, typical solar-generated electricity is inferior to "base load" generating resources, such as coal, nuclear, and geothermal, which reliably provide electricity around the clock, and "dispatchable" resources, such as hydroelectric and gas-fired, which provide varying capacities in response to fluctuating load.

[0029] A conventional device which addresses this defect is the "power tower" design (see **FIG. 6**) for a solar electric generating plant combined with thermal storage, whereby numerous mirrors are placed in a field, each equipped with two-axis tracking devices which enable all the mirrors to concentrate solar radiation on a heat exchanger located in a tower high above the field of mirrors. By achieving high levels of concentration of the radiation, high temperatures can be achieved in the heat exchanger. A medium suitable for storing heat in a high ratio of energy stored to volume, such as salt, can be circulated through the heat exchanger, then stored, typically in molten form, and later used to generate electricity, for example by producing steam to drive a steam turbine. Typically, this enables the solar generating plant to perform as a base load resource. It also enables the solar generating plant to perform as a peaking resource.

[0030] The power tower design suffers from defects of technical complexity and high cost. The technical complexity and high cost arise from the following, among other factors:

1) Each mirror must be precisely parabolic, in order to aim the reflected sunlight at a small heat exchanger a significant distance away. Because of the substantial distance between the mirrors and the heat exchanger, small errors in the parabolic shape of the mirror will result the reflected sunlight not being concentrated on the heat exchanger. This requires relatively exacting and expensive fabrication techniques and quality control.

2) Each mirror must be highly reflective. This requires the use of expensive materials, such as silver, coating the reflective surface.

3) Each mirror must be kept very clean and free of dust. This requires frequent maintenance.

4) Each mirror must be highly accurate in reflecting the solar radiation, hitting a small target (the heat exchanger) at a large distance away. Because of the substantial distance between the mirrors and the heat exchanger, small aiming errors will result the reflected sunlight missing the heat exchanger and even harming nearby activities. This low-tolerance aiming requires high-precision, and consequently high cost, tracking equipment. It also requires almost constant adjustment of the mirror's orientation, making it effectively necessary that each mirror have two dedicated motors, one each for azimuth and altitude.

5) The heat exchanger must be mounted high on a tower, in order enable a large field of mirrors to "see" the heat exchanger. This requires the capital cost of the tower and the piping to bring the storage medium to the location of the generating equipment. It also requires maintenance personnel to mount the tower in order to perform maintenance activities.

6) Each mirror must have its own algorithm for aiming, since the reflective angle connecting each mirror to the heat exchanger is unique.

7) Because the aiming of the mirrors must be very precise, the mounting of the mirrors must be highly resistant to wind load, which will affect the shape and aim of the mirrors. This means that each mirror must be structurally robust enough to resist deflection under load, increasing its weight and cost, and the mounting of each mirror must secure the mirror precisely in position, increasing the weight and cost of the mounting equipment.

[0031] A second typical defect of solar generating technologies is capital cost. In particular, photovoltaic generation, the most common form of solar-generated electricity is expensive. U.S. Pat. No. 8,412,010 B2, Ghosh, *et al.*, purports to address this defect using the principle of total internal reflection (TIR) to capture solar radiation which is incident to the surface of a transparent medium such as an acrylic panel and redirect it through the transparent medium toward one edge or a radial concentration region of the medium, where a small photovoltaic element receives the concentrated radiation. Typically, radiation passes approximately perpendicularly through the surface of a transparent panel and encounters a series of planar boundaries of the medium at angles of incidence within the numerical aperture of the material, that is, at angles less than that at which TIR occurs. This results in the directing of 100% of the radiation into a "wave guide", through which it can pass to an edge or to the center of the medium. A photovoltaic element is typically positioned at that downstream edge or center of the medium. The cost of the transparent medium is typically lower than the cost of the photovoltaic element, so the overall cost per KW of captured radiation is reduced.

[0032] The current invention is superior to the wave guide design in prior art because it produces electric power that is fully dispatchable and is superior to the power tower design in that it is simpler to design and operate, less expensive to manufacture, more tolerant of operating errors and environmental conditions, and more readily scalable. Specifically, it achieves the high concentration ratios of, or higher concentration ratios than, the power tower design and includes numerous advantages over the power tower design.

[0033] The invention can be implemented in numerous ways, including as a process; an apparatus; a system; a composition of matter; a computer program product embodied on a computer readable storage medium; and/or a processor, such as a processor configured to execute instructions stored on and/or provided by a memory coupled to the processor. In this specification, these implementations, or any other form that the invention may take, may be referred to as techniques. In general, the order of the steps of disclosed processes may be altered within the scope of the invention. Unless stated otherwise, a component such as a processor or a memory described as being configured to perform a task may be implemented as a general component that is temporarily configured to perform the task at a given time or a specific component that is manufactured to perform the task. As used herein, the term `processor` refers to one or more devices, circuits, and/or processing cores configured to process data, such as computer program instructions.

[0034] A detailed description of one or more embodiments of the invention is provided below along with accompanying figures that illustrate the principles of the invention. The invention is described in connection with such embodiments, but the invention is not limited to any embodiment. The scope of the invention is limited only by the claims, and the invention encompasses numerous alternatives, modifications, and equivalents. Numerous specific details are set forth in the following description in order to provide a thorough understanding of the invention. These details are provided for the purpose of example, and the invention may be practiced according to the claims without some or all of these specific details. For the purpose of clarity, technical material that is known in the technical fields related to the invention has not been described in detail so that the invention is not unnecessarily obscured.

The Embodiments

[0035] In various embodiments, the present invention uses the principle of total internal reflectance (TIR) to capture radiation which is incident to the surface of a transparent medium and redirect it through the wave guide region of the transparent medium toward one edge or radial concentration region of the medium. Unlike conventional devices, the present invention uses three concentration steps to create a low-complexity, low-capital-cost method of achieving high concentrations of incoming radiation, then using the thrice-concentrated radiation to drive a storage-based generating station. At the downstream edge or region of the radiation-capturing transparent medium to which the radiation is directed in the first step of concentration, a second linear element of radiation-capturing transparent medium with wave guide is placed, achieving a second step of concentration. In essence, the first step concentrates the incoming radiation from an area to a line (either a straight line or a curved line representing the concentrating region of a radial wave guide), and the second step concentrates the radiation from a line to a point (or more precisely, to a small region where all the radiation is within the numerical aperture on a single dimension). In an exemplary embodiment, in which a ratio of about 5:1 concentration in each of the steps (an area of the panel to a line, a line to a point), a concentration ratio of about 25:1 will be achieved in each optical concentrator.

[0036] In an exemplary embodiment, the invention provides a device for collecting and storing solar energy, the device comprising: (a) an optical concentrator configured to receive incident solar radiation and conduct the incident solar radiation to a means for transmission of the received solar radiation to an energy recovery device, wherein the optical concentrator and the energy recovery device are operatively connected through the transmission means.

[0037] The present invention uses the principle of total internal reflection (TIR) to capture radiation which is incident to the surface of a transparent medium and redirect it through the wave guide region of the transparent medium toward one edge or radial concentration region of the medium, as in prior art. However, rather than using one or two steps of concentration of radiation directed at a photovoltaic element as in prior art, the present invention uses three concentration steps to create a low-complexity, low-capital-cost method of achieving high concentrations of incoming radiation, then using the thrice-concentrated radiation to drive a storage-based generating station. At the downstream edge or region of the radiation-capturing transparent medium to which the radiation is directed in the first step of concentration, a second linear element of radiation-capturing transparent medium with wave guide is placed, achieving a second step of concentration. In essence, the first step concentrates the incoming radiation from an area to a line (either a straight line or a curved line representing the concentrating region of a radial wave guide), and the second step concentrates the radiation from a line to a point (or more precisely, to a small region where all the radiation is within the numerical aperture on a single dimension).

[0038] The current invention is superior to the wave guide design in prior art because it produces electric power that is fully dispatchable and is superior to the power tower design in that it is simpler to design and operate, less expensive to manufacture, more tolerant of operating errors and environmental conditions, and more readily scalable. Specifically, it achieves the high concentration ratios of, or higher concentration ratios than, the power tower design and includes the following further advantages over the power tower design:

1) The panels need to track the sun with a single tracking algorithm for all panels in a plant, making the tracking mechanism less complex and expensive. As discussed above, conventional power tower designs have different tracking algorithms for every mirror.

2) Since all panels have the same orientation, two motors (one each for azimuth and altitude) can control a plurality of panels. As discussed above, conventional power tower designs require almost constant adjustment of the mirror's orientation, making it effectively necessary that each mirror have two dedicated motors, one each for azimuth and altitude.

3) In contrast to power tower designs, the tracking device does not need to track the sun very accurately; the TIR wave guide technique can function effectively if the angle of incidence is only approximately perpendicular. Therefore, the tracking mechanism can be relatively low-tech and inexpensive.

4) Because of this aiming tolerance, and in contrast to power tower designs, the panels can effectively collect and concentrate sunlight with much less frequent aiming adjustments, enabling a pair of motors to migrate between panels for purposes of orientation.

5) This tolerance of imprecise tracking angles makes the performance of the plant robust even if the panels are somewhat deformed by wind loads; this enables the support mechanisms to be less robust structurally, lighter and made of less expensive and less precisely fabricated materials.

6) The effectiveness of the panels will degrade less quickly than mirrors as a result of accumulated dirt and surface pitting.

7) The materials from which the panels and fiber optic cables are made are inexpensive (acrylic and glass), as opposed to the use of highly reflective materials such as silver in the power tower design's mirrors.

8) The manufacturing tolerances of the panels are much less exacting, in contrast to the precisely parabolic shape of the power tower's mirrors.

9) Because there is no need to build a tower to receive reflected radiation from a field of mirrors, the heat exchanger can be located at ground level, where support, foundation, weather protection, and maintenance are easier and less expensive.

10) The field can be scaled up easily, without the limitation of having to connect the mirror field with the heat exchanger optically, so it is feasible to have large concentration ratios and large generating capacities in a single plant.

[0039] The invention is further described by reference to the figures attached hereto. **FIG. 1A** and **FIG. 1B** show, respectively, a plan view and an isometric view of an exemplary solar concentrator of the invention. Solar radiation enters the device through primary collection region **1**. In an exemplary embodiment, radiation passes approximately perpendicularly through the surface of a transparent panel and encounters a series of planar boundaries of the medium at angles of incidence within the numerical aperture of the material, that is, at angles less than that at which TIR occurs. This results in the directing of 100% of the radiation into a "wave guide", through which it can pass to an edge or to the center of the medium.

[0040] In an exemplary embodiment, the incident radiation is shifted approximately 90 degrees within the device and it is transmitted to secondary collection region **2**, where it is shifed approximately another 90 degrees. The concentrated radiation in the second collection region is transmitted to a transmission means **3**, and hence to an energy recovery device (not shown). The letter A designates the location where the section is cut in **FIG. 2**.

[0041] An exemplary optical concentrator of use in the invention is fabricated from a transmissive material that guides incident light to a focal area coinciding with the interface between the primary and secondary collection regions. In some embodiments, the optical concentrator comprises a waveguide. In some embodiments, the optical components form a concentrator optic. In some embodiments, the optical components form an ATIR (Aggregated Total Internal Reflection) optic. In some embodiments, the optical components comprise a concentrating layer that concentrates incident light and/or a waveguide layer that aggregates concentrated light and conveys it to a focal area. In some such cases, for example, integrated optical features in the primary collection region are responsible for concentrating light, and the secondary collection region is responsible for redirecting, aggregating, and/or conveying concentrated light to a focal area. In some embodiments, the secondary collection region may further concentrate light received from the primary collection region. In some embodiments, the optical concentrator comprises the type of concentrator optics disclosed in U.S. patent application Ser. Nos. 11/852,854 and 12/207,346.

[0042] **FIG. 2A** shows Section A through the solar concentrator of **FIG. 1A** and **FIG. 1B**. Incident solar radiation R1 enters the first collection region **1** and is shifted approximately 90 degrees by interaction with aperatures **20** in the body of the first collection region. The shifted radiation is transmitted to second collection region **2**. **FIG. 2B** shows the plurality of aperatures **20** within the first collection region.

[0043] **FIG. 3A** is a plan view of the solar concentrator with the detail of the aperatures of the waveguide in the secondary collection region shown. **FIG. 3B** shows the incident solar radiation R1 being shifted by approximately 90 degrees in the second collection region **2** and being transmitted to the transmission means **3**. The radiation in the secondary collection region is within the numerical aperature with respect to axis x. The radiation is transmitted through the transmission means **3** to the energy recovery device (not shown). In an exemplary embodiment, the transmission means includes a tapered section **5**.

[0044] In an exemplary embodiment, the transmission means **3** is a fiber optic cable. The taper in the fiber optic output cable is limited so as to keep the radiation R3 within the numerical aperture with respect to axis X and with respect to the long axis of the fiber optic cable. (Negative taper, where the downstream cable is larger than the upstream cable and the output of the upstream cable is entirely contained by the input of the downstream cable, is inconsequential). The cross-sectional area of the cable after tapering is limited by the opacity of the cable. Light transmitting materials are not perfectly transparent. Any slight opacity in the material will absorb light, converting it to heat. The cross-sectional area of the light transmitting materials is preferably adequate to prevent excessive heat buildup.

[0045] In an exemplary embodiment, the ratio of concentration is about 5:1 concentration in at least one step (i.e., an area of the panel to a line, a line to a point). In various embodiments, the ratio of concentration is about 5:1 in each of the steps. In this embodiment, the ratio of concentration ratio is about 25:1 in each panel.

[0046] Thus, in an exemplary embodiment, the device of the invention includes an optical concentrator comprising a primary collection region for receiving the incident solar radiation at a first angle, shifting the received solar radiation within the panel to a second angle, transmitting the solar radiation shifted to the second angle to a secondary collection region in operative communication with the primary collector panel, said secondary collector component, shifting the solar radiation at a second angle to a third angle.

[0047] In an exemplary embodiment, the secondary collection region is in operative communication with the transmission means

[0048] In various embodiments, the materials from which the concentrator and fiber optic cables are made are inexpensive (acrylic and glass), as opposed to the use of highly reflective materials such as silver in the power tower design's mirrors.

[0049] In various embodiments, the panels of the device degrade less quickly than mirrors as a result of accumulated dirt and surface pitting.

[0050] In various embodiments, the manufacturing tolerances of the panels are much less exacting, in contrast to the precisely parabolic shape of the power tower's mirrors.

[0051] In various embodiments, because there is no need to build a tower to receive reflected radiation from a field of mirrors, the heat exchanger can be located at ground level, where support, foundation, weather protection, and maintenance are easier and less expensive.

[0052] In various embodiments, the field can be scaled up easily, without the limitation of having to connect the mirror field with the heat exchanger optically, so it is feasible to have large concentration ratios and large generating capacities in a single plant.

[0053] The concentrated energy is transferred to the energy recovery device through a transmission means. In an exemplary embodiment, the transmission means is a fiber optic device, e.g., a fiber optic cable.

[0054] The device of the invention is not utilized to convert solar energy directly to electricity, rather the energy is stored in the energy recovery device and the stored energy is utilized to generate electricity. Thus, in various embodiments, a member selected from the primary collection region, the secondary collection region, the transmission means and a combination thereof is not configured to convert the solar radiation directly into electricity.

[0055] In various embodiments, a member selected from the primary collection region, the secondary collection region, the transmission means and a combination thereof is not a photovoltaic.

[0056] Unlike conventional power towers, the present invention does not make use of a mirror to direct energy to the energy recovery device. Thus, in various embodiments, a member selected from the primary collector panel, the secondary collector, the transmission means and a combination thereof is not a mirror.

[0057] The energy recovery device contains a heat storage medium to which the concentrated solar radiation is transferred for storage. Many exemplary heat storage media are known and are of use in the present invention. In an exemplary embodiment, the heat storage medium is a salt. The heat storage medium stores the energy as a member selected from sensible energy, phase transition energy and a combination thereof.

[0058] In an exemplary embodiment, the energy recovery device is operatively connected to a device for converting the energy to work. In an exemplary embodiment, the energy recovery device is operatively connected to a device for converting the energy to electricity. The invention is not limited by the structure or principle of operation of the device for converting the energy to electricity.

[0059] The use of high temperature molten salt and a thermally insulated storage tank enables the collection and storage system of the invention to provide electricity (and heat energy) up to 24 hours a day and to operate at sufficiently high temperatures so that the heat energy can be used in a reasonably efficient manner to operate an electricity generating device such as a steam turbine.

[0060] An exemplary high temperature solar power system includes a molten salt heat transfer medium, a high temperature energy recovery device, and an energy conversion system. The molten salt heat storage medium is capable of being heated to high temperatures, for example, a temperature of at least approximately 1200° F by the high temperature energy recovery device. The energy conversion system uses thermal energy from the molten salt heat storage medium to generate power.

[0061] Storing solar thermal technology consists of using solar radiation to heat a heat storage fluid acting as a heat source in a thermodynamic cycle. Concentration makes it possible to reach temperatures of varying levels and thus benefit from varying degrees of thermodynamic conversion efficiency.

[0062] In an exemplary embodiment, the energy recovery device includes a plurality of juxtaposed tubes wherein the transfer fluid circulates, a portion of the surface of these tubes collecting the solar radiation with juxtaposed tubes. This technique is particularly suitable when the transfer fluid is a liquid, such as liquid water, oil or molten salts. In an exemplary embodiment, the energy recovery device uses liquid metals as the heat storage fluid and can reach temperatures of approximately 1600° F, or and molten salts, which can reach temperatures of approximately 1100° F.

[0063] In an exemplary embodiment, after the heat transfer fluid has been heated in the energy recovery device, the heat transfer storage medium flows into the hot thermal storage tank. The heat storage medium is then stored in the hot thermal storage tank until it is needed for electrical power generation. The hot thermal storage tank allows for electrical power production that is not concurrent with the availability of sunlight. When electrical energy is needed, the heated heat storage medium is pumped from the hot thermal storage tank and circulated through the energy conversion system. The heat transfer fluid transfers the heat within the energy conversion system. The energy conversion system can be, for example, a Rankine cycle conversion system or a Brayton cycle conversion system. After the heat has been removed from the heat storage medium, the heat storage medium is transported back to the cold storage tank for reuse. In general, the higher the temperature of the heat storage medium, the more efficient the power generating system. Thus, heat storage media and systems capable of withstanding higher temperatures are desirable.

[0064] In an exemplary embodiment, the invention provides a method of collecting and storing solar energy. The method can utilize a device of the invention. An exemplary method includes (a) collecting incident solar radiation in an optical concentrator configured to concentrate the solar energy to a beam focused for transmission through a transmission means into an energy recovery device; and (b) transmitting the beam through the transmission means to the energy recovery device, transferring energy stored in the beam to the energy recovery device, thereby storing the energy. The optical concentrator and the energy recovery device are operatively linked through the transmission means.

[0065] The method of the invention does not convert solar energy directly to electricity, rather the energy is stored in the energy recovery device, and the stored energy is transferred to an electricity generating device where it is converted to energy. Thus, in an exemplary embodiment, neither step (a) nor step (b) includes using a photovoltaic or a mirror.

[0066] In an exemplary embodiment, the invention provides a system for collecting and storing solar energy. The system comprises a plurality of optical concentrators, each of which is configured to receive incident solar radiation and conduct the received solar radiation to a transmission means for transmitting the received solar radiation to an energy recovery device, wherein each of the optical concentrators is operatively connected to the energy recovery device through the transmission means.

[0067] For example, several panels based on the invention are caused to track the movement of the sun on two axes, so that incident solar radiation is concentrated in two steps and directed into fiber optic cables. All such fiber optic cables carry radiation from the collection of panels in the plant to a single heat exchanger and concentrate the radiation on the heat exchanger. Assuming a 5:1 ratio in each of the first two steps and 100 panels in a plant, an overall concentration ratio of 2,500:1 is achieved.

[0068] The system may be configured in any useful arrangement and the components may be isolated or linked in a manner that enhances the efficiency of energy collection and storage.

[0069] In an exemplary embodiment, a plurality of panels collect and concentrate radiation, with each panel directing the concentrated radiation from the second step wave guide into a further wave guide, such as a fiber optic cable. The radiation thus collected into two or more wave guides is directed onto a single point of use, achieving a third step of concentration. The thrice concentrated radiation from the third embodiment is directed at a heat exchanger in order to generate high temperatures suitable for a heat storage medium such as molten salt, which after heating is then stored for later use, as in the power tower design of prior art. For example, several panels based on the invention are caused to track the movement of the sun on two axes, so that incident solar radiation is concentrated in two steps and directed into fiber optic cables. All such fiber optic cables carry radiation from the collection of panels in the plant to a single energy recovery device and concentrate the radiation on the energy recovery device.

[0070] **FIG. 4** shows a section of an exemplary system of the invention. In this system, solare concentrators include a primary collection region **1**, a secondary collection region **2** and a transmission means **3**. The transmission means from a first solar concentrator and a second solar concentrator are operatively linked togther in a first linkage **7**. In an exemplary embodiment, two or more first linkages are linked together in a second linkage **8**.

[0071] **FIG. 5** shows a plan view of a system of the invention and an exploded view of an exemplary energy recovery device of use in the invention. In this embodiment, energy transmitted through transmission means **3**, **7** and **8** is delivered to energy recovery device **6**. An exemplary recovery device includes the transmission means **3** operatively connected with the recovery device. An exemplary device of the invention includes downstream transmission means **15**, which connect(s) the transmission means from the plurality of optical concentrators to the energy recovery device **6**, thereby transmitting the collected and concentrated radiation to the heat storage medium. An exemplary energy recovery device of use in the invention includes a heat resistant container **16**, charged with heat storage medium **17**. The container is optionally surrounded with insulation **18**.

[0072] In an exemplary embodiment, each optical concentrator provides about a 5:1 concentration ratio in each of the first two steps, thus, in an exemplary system with 100 optical concentrators, an overall concentration ratio of 2,500:1 is achieved.

[0073] In various embodiments, the device further includes a means of orienting the position of an upper surface of the optical concentrator. In an exemplary embodiment, the orienting means is configured to orient the position of the upper surface altitudinally, azimuthally and a combination thereof. An exemplary orienting means is a motor.

[0074] In an exemplary embodiment, the panels track the sun with a single tracking algorithm for all panels in a plant, making the tracking mechanism less complex and expensive. This is a significant benefit of the present invention. By comparison, conventional power tower designs have different tracking algorithms for every mirror.

[0075] In various embodiments, all panels have the same orientation, thus, two motors (one each for azimuth and altitude) are sufficient to control a plurality of panels. As discussed above, conventional power tower designs require almost constant adjustment of the mirror's orientation, making it effectively necessary that each mirror have two dedicated motors, one each for azimuth and altitude.

[0076] In various embodiments, in contrast to power tower designs, the tracking device does not need to track the sun with a high degree of accurately; the TIR wave guide technique can function effectively if the angle of incidence is only approximately perpendicular. Therefore, the tracking mechanism can be relatively low-tech and inexpensive.

[0077] In various embodiments, the device is tolerant of inaccuracies in aiming as discussed above, and in contrast to power tower designs, the panels can effectively collect and concentrate sunlight with much less frequent aiming adjustments, enabling a pair of motors to migrate between panels for purposes of orientation. This tolerance of imprecise tracking angles makes the performance of the plant robust even if the panels are somewhat deformed by wind loads; this enables the support mechanisms to be less robust structurally, lighter and made of less expensive and less precisely fabricated materials.

[0078] In an exemplary embodiment, the device, system and method of the invention utilized an energy recovery device that contains a high temperature molten salt. The use of high temperature molten salt and hot thermal storage tank enables the system of the invention to provide electricity (and heat energy) up to 24 hours a day and to operate at sufficiently high temperatures so that the heat energy can be used in a reasonably efficient manner to operate a gas turbine, simplifies solar power conversion systems, and reduces system dependency on water when compared to other cycles, such as Rankine steam cycles.

[0079] In an exemplary embodiment, the heat storage medium is stored in a cold storage tank. When needed, the heat storage medium is pumped to energy recovery device **4**, which is heated by solar radiation reflected from a field of multiple optical concentrators. In various embodiments, the energy recovery device is capable of withstanding high temperatures, for example, temperatures of at least approximately 1200° F, preferably at least approximately 1500° F, more preferably at least approximately 1700° F, and most preferably at least approximately 1800° F. Suitable materials for constructing the energy recovery device include, but are not limited to: nickel based alloys, iron based alloys, and cobalt based alloys. Examples of suitable commercially available nickel based alloys include: Hastelloy X, Hastelloy N, Hastelloy C, and Inconel 718, available from Special Metals Inc., Conroe, Tex. Examples of suitable commercially available iron based alloys include: A-286 and PM2000, available from Metallwerke Plansee, Austria. An example of a suitable commercially available cobalt based alloy includes: Haynes 25, available from Haynes International Inc., Windsor, Conn.

[0080] After the heat storage medium has been heated to its desired temperature, the heat storage medium is pumped to hot storage tank, where it is stored until needed by energy conversion system. The heated heat storage medium is pumped to an energy conversion system to generate power. In an exemplary embodiment, the system of the invention is used in conjunction with an air Brayton cycle conversion system as energy conversion system. The use of a Brayton cycle conversion system as the energy conversion system eliminates the need for a steam Rankine cycle conversion system, reducing a significant amount of plant equipment. For example, a steam generator system, steam turbine, electric generator, cooling tower, water purification equipment, steam drum, aerator, water treatment system, and make-up water are no longer necessary. Use of an air Brayton cycle conversion system with a solar power tower system is described in U.S. Pat. No. 6,957,536 (Litwin et al.).

[0081] After the heat storage medium has passed through energy conversion system, the extracted thermal energy results in a drastic drop in the heat storage medium temperature and it is sent back to the cold storage tank. The heat storage medium is reused in a closed cycle power system and is stored in the cold storage tank until needed.

[0082] In an exemplary embodiment, the heat storage medium is a molten salt capable of being heated to high temperatures. The molten salt used to store heat from the optical concentrator is capable of being heated to high temperatures, for example, to a temperature of at least approximately 1200° F, preferably at least approximately 1500° F, more preferably at least approximately 1700° F, and most preferably at least approximately 1800° F. The molten salt can be salts composed of alkaline earth fluorides and alkali metal fluorides, and combinations thereof. Suitable elements of the molten salt include: Lithium (Li), Sodium (Na), Potassium (K), Rubidium (Rb), Cesium (Cs), Francium (Fr), Beryllium (Be), Magnesium (Mg), Calcium (Ca), Strontium (Sr), Barium (Ba), Radium (Ra), and Fluorine (F). Examples of suitable fluoride molten salts include, but are not limited to: FLiNaK, FLiBe, FLiNaBe, FLiKBe, and combinations thereof.

[0083] Suitable component concentrations in the composition of FLiNaK range from about 10 mol % to about 90 mol % LiF, about 1 mol % to about 30 mol % NaF, and about 10 mol % to about 90 mol % KF. Particularly suitable component concentrations in the composition of the present invention range from about 44 mol % to about 48 mol % LiF, about 9 mol % to about 12 mol % NaF, and about 40 mol % to about 44 mol % KF. Those skilled in the art will appreciate other suitable component concentration ranges for obtaining comparable physical properties of the molten salt.

[0084] Suitable component concentrations in the composition of FLiBe range from about 10 mol % to about 90 mol % LiF and about 10 mol % to about 90 mol % BeF_2. Particularly suitable component concentrations in the composition of the present invention range from about 44 mol % to about 48 mol % LiF and about 52 mol % to about 56 mol % BeF_2. Those skilled in the art will appreciate other suitable component concentration ranges for obtaining comparable physical properties of the molten salt.

[0085] Suitable component concentrations in the composition of FLiNaBe range from about 10 mol % to about 90 mol % BeF_2, about 10 mol % to about 90 mol % NaF, and about 10 mol % to about 90 mol % LiF. Particularly suitable component concentrations in the composition of the present invention range from about 25 mol % to about 35 mol % $NaBeF_4$ and about 65 mol % to about 75 mol % Li_2BeF_4. Those skilled in the art will appreciate other suitable component concentration ranges for obtaining comparable physical properties of the molten salt.

[0086] Suitable component concentrations in the composition of FLiKBe range from about 10 mol % to about 90 mol % KF, about 10 mol % to about 90 mol % LiF, and about 10 mol % to about 90 mol % BeF_2. Those skilled in the art will appreciate other suitable component concentration ranges for obtaining comparable physical properties of the molten salt.

[0087] The foregoing description of embodiments of the present invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the present invention to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the present invention. The embodiments were chosen and described in order to explain the principles of the present invention and its practical application to enable one skilled in the art to utilize the present invention in various embodiments, and with various modifications, as are suited to the particular use contemplated.

[0088] The disclosures of each and every patent, patent application, and publication cited herein are hereby incorporated herein by reference in their entirety.

WHAT IS CLAIMED IS:

1. A device for collecting and storing solar energy, the device comprising: (a) an optical concentrator configured to receive incident solar radiation and conduct the incident solar radiation to a means for transmission of the received solar radiation to an energy recovery device, wherein the optical concentrator and the energy recovery device are operatively connected through the transmission means.

2. The device according to claim 1, wherein the optical concentrator is a panel of material characterized by total internal reflection.

3. The device according to claim 1, wherein the optical concentrator is a panel of a material selected from acrylic polymer and glass.

4. The device according to claim 1, wherein the transmission means is a fiber optic device.

5. The device according to claim 1, wherein the energy recovery device contains a heat storage medium.

6. The device according to claim 5, wherein the heat storage medium is a salt.

7. The device according to claim 1, wherein the optical concentrator comprises a primary collection region for receiving the incident solar radiation at a first angle, shifting the received solar radiation within the panel to a second angle, transmitting the solar radiation shifted to the second angle to a secondary region in operative communication with the primary collection region, said secondary collection region shifting the solar radiation at a second angle to a third angle.

8. The device according to claim 7, wherein the secondary collection region is in operative communication with the transmission means.

9. The device according to claim 1, wherein the energy recovery device is operatively connected to a device for converting the energy to work.

10. The device according to claim 1, wherein the energy recovery device is operatively connected to a device for converting the energy to electricity.

11. The device according to claim 1, further comprising a means of orienting the position of an upper surface of the optical concentrator.

12. The device according to claim 10, wherein the orienting means is configured to orient the position of the upper surface altitudinally, azimuthally and a combination thereof.

13. The device according to claim 11, wherein the orienting means is a motor.

14. The device according to claim 1, wherein a member selected from the primary collection region, the secondary collection region, the transmission means and a combination thereof is not a photovoltaic.

15. The device according to claim 1, wherein a member selected from the primary collection region, the secondary collection region, the transmission means and a combination thereof is not configured to convert the solar radiation directly into electricity.

16. The device according to claim 1, wherein a member selected from the primary collection region, the secondary collection region, the transmission means and a combination thereof is not a mirror.

17. A system for collecting and storing solar energy, comprising a plurality of optical concentrators, each of which is configured to receive incident solar radiation and conduct the received solar radiation to a transmission means for transmitting the received solar radiation to an energy recovery device, wherein each of the optical concentrators is operatively connected to the energy recovery device through the transmission means.

18. The system according to claim 17, comprising a single energy recovery device operatively attached to each member of the plurality of optical concentrators through the transmission means.

19. The system according to claim 17, wherein the transmission means of a first member of the plurality is connected to the transmission means of a second member of the plurality.

20. A method of collecting and storing solar energy, comprising:

(a) collecting incident solar radiation in an optical concentrator configured to concentrate the solar energy to a beam focused for transmission through a transmission means into an energy recovery device; and

(b) transmitting the beam through the transmission means to the energy recovery device, transferring energy stored in the beam to the energy recovery device, thereby storing the energy,

wherein the optical concentrator and the energy recovery device are operatively linked through the transmission means.

21. The method according to claim 20, wherein neither step (a) nor step (b) includes using a photovoltaic or a mirror.

22. The method according to claim 20, wherein the stored energy is transferred to a device for generating electricity.

23. The method according to claim 20, wherein the heat storage medium stores the energy as a member selected from sensible energy, phase transition energy and a combination thereof.

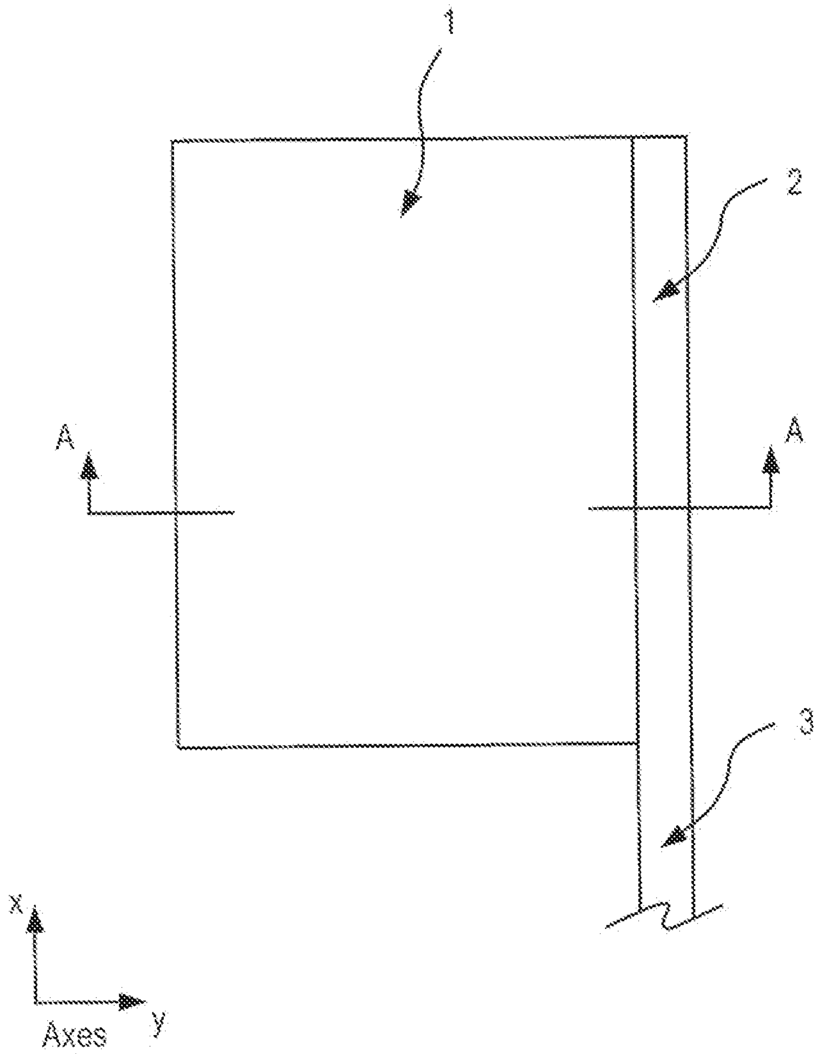

FIG. 1A

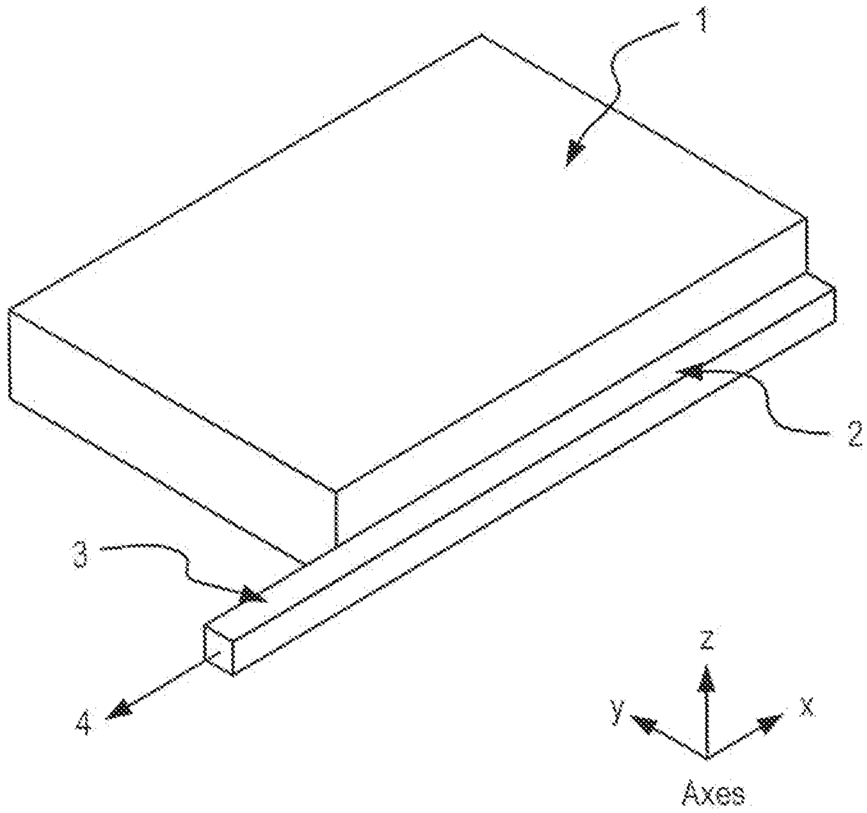

FIG. 1B

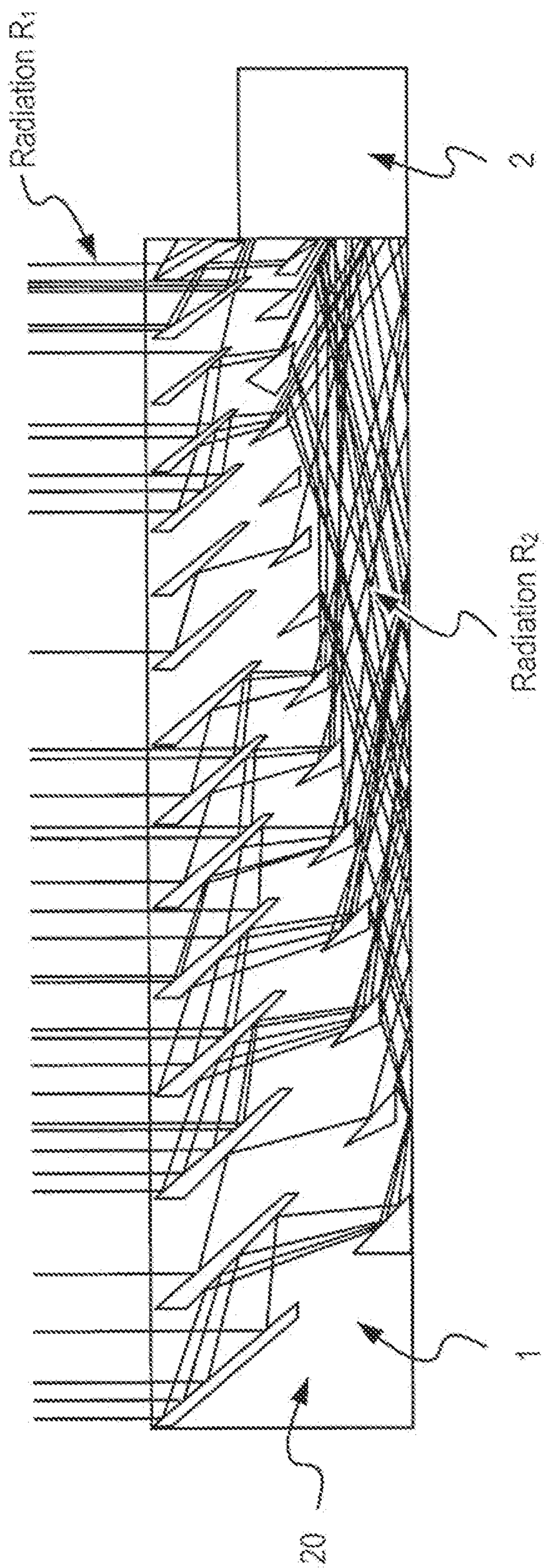

FIG. 2A

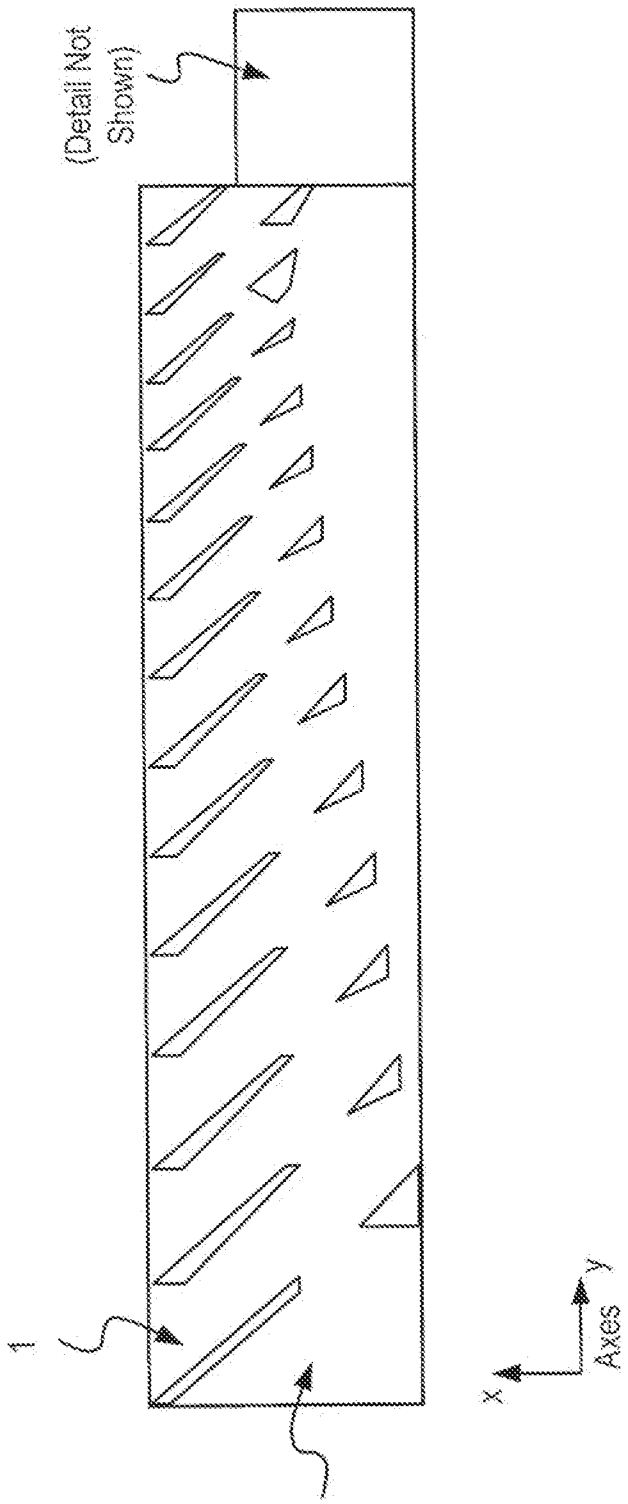

FIG. 2B

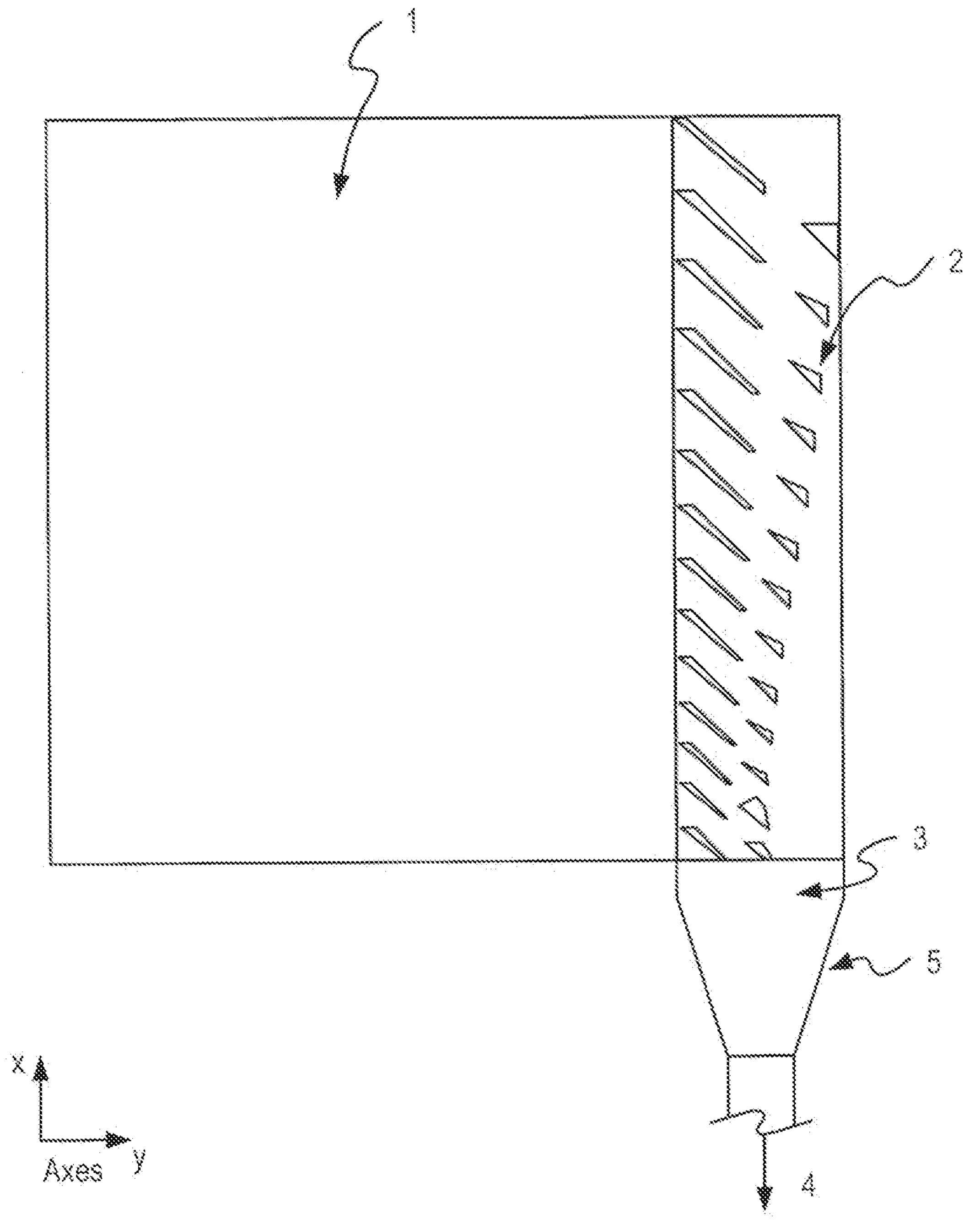

FIG. 3A

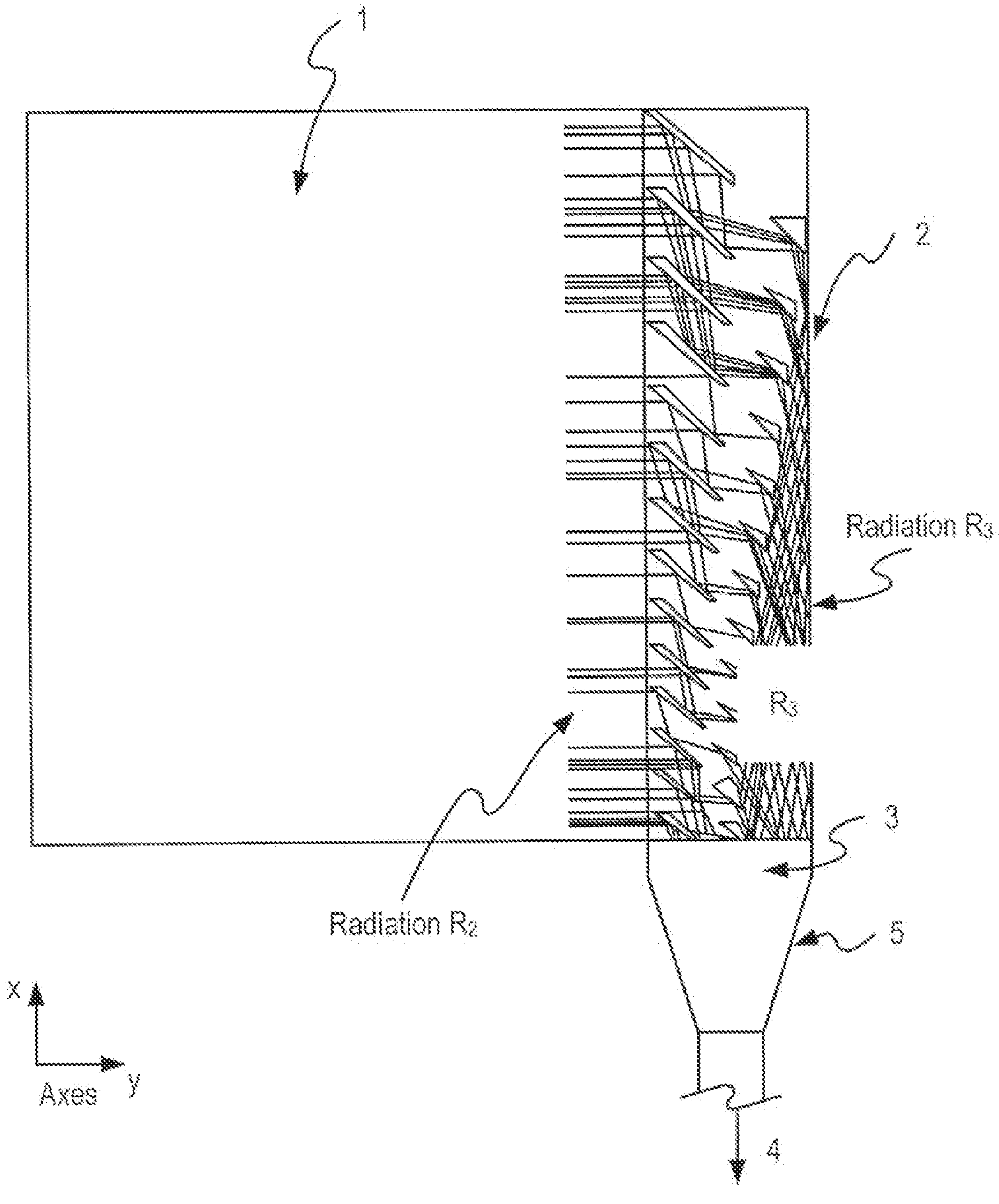

FIG. 3B

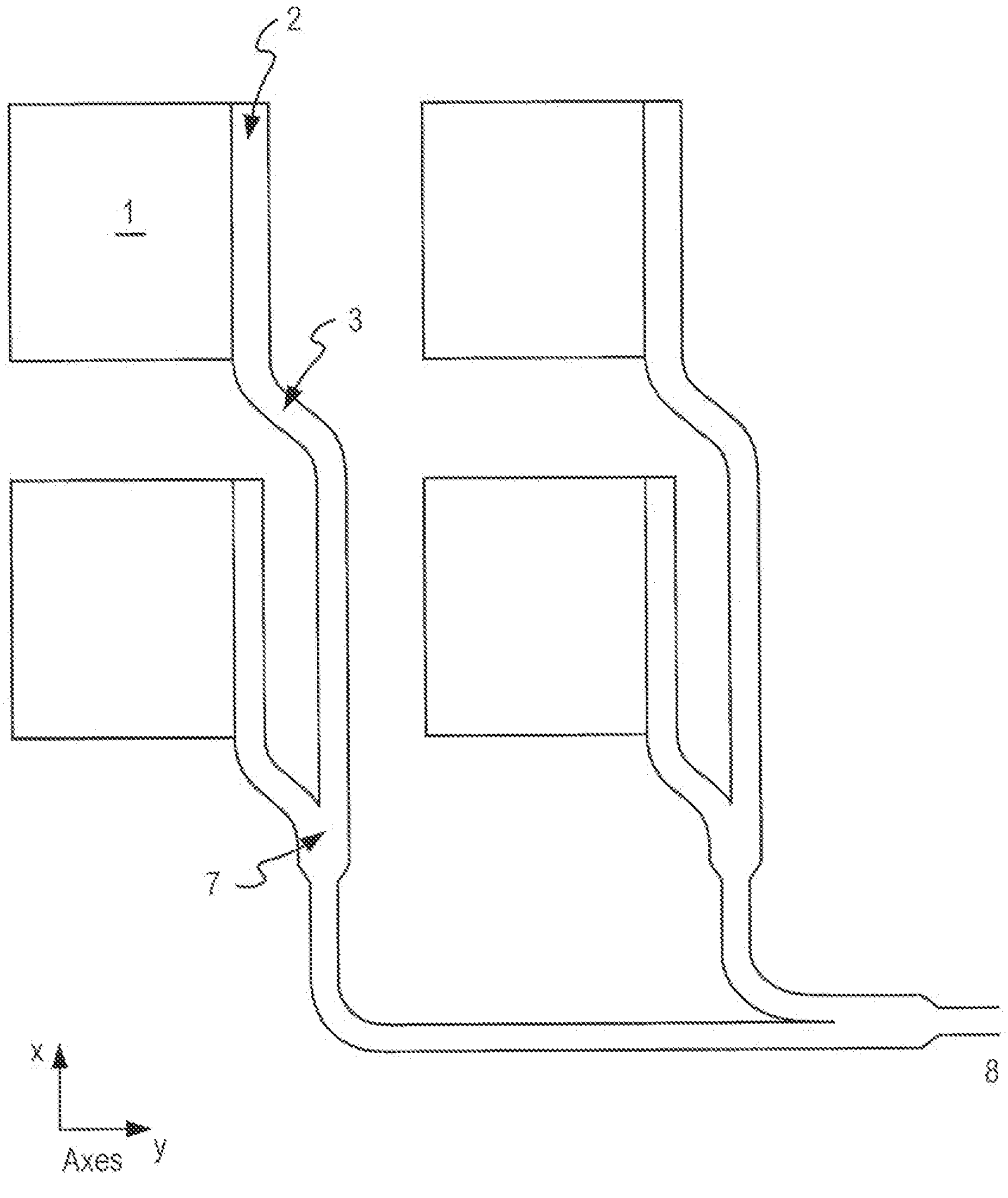

FIG. 4

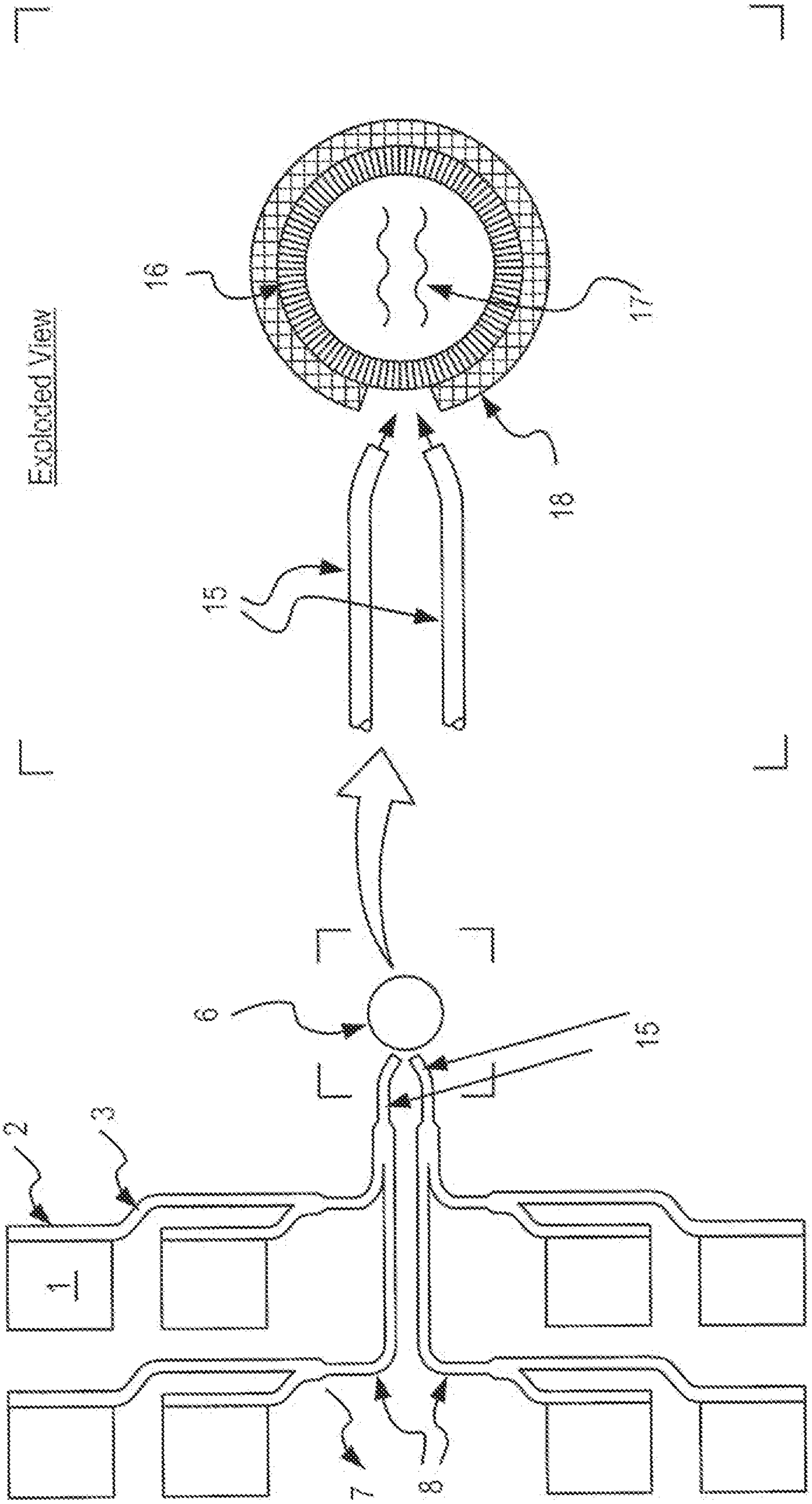

FIG. 5

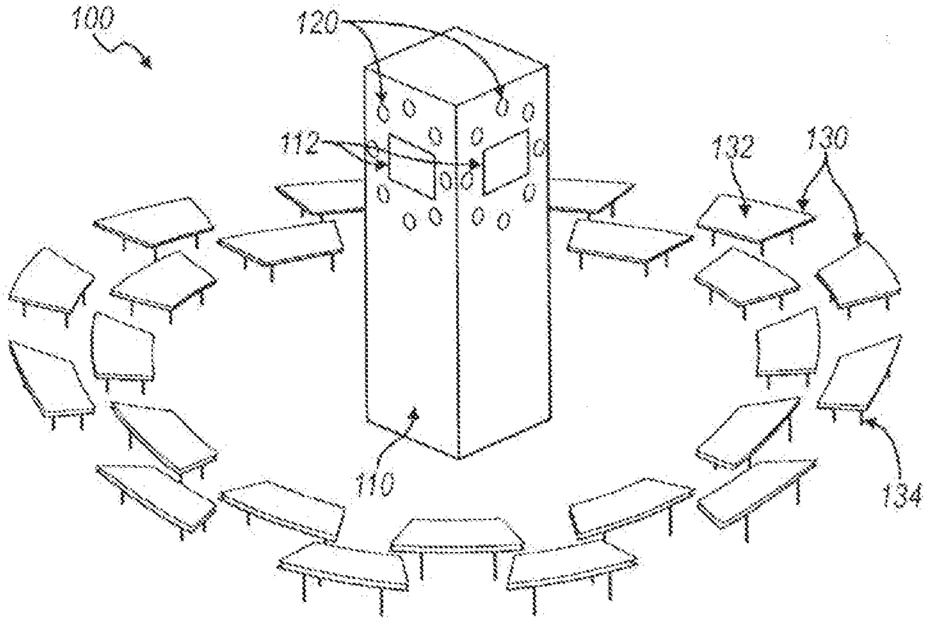

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/062424

A. CLASSIFICATION OF SUBJECT MATTER

H01L 31/042(2006.01)i, H01L 31/052(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01L 31/042; F24J 2/46; F24J 2/38; G02B 5/10; F24J 2/10; H01L 31/052; F24J 2/08; F24J 2/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: solar energy, concentrator, transmission, heat storage medium, total internal reflection

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011-0079267 A1 (MARK A. RAYMOND et al.) 07 April 2011 See paragraphs [0037]-[0063]; and figures 1-5.	1-23
A	US 2010-0212719 A1 (HANS-HENRIK KOFOED STOLUM) 26 August 2010 See paragraphs [0040]-[0132]; and figures 1-16.	1-23
A	US 2010-0319678 A1 (TOSHIHIKO MAEMURA et al.) 23 December 2010 See paragraphs [0055]-[0088]; and figures 1-11.	1-23
A	US 2012-0019942 A1 (JOHN PAUL MORGAN) 26 January 2012 See paragraphs [0125]-[0228]; and figures 1-72.	1-23
A	WO 2010-118038 A1 (DONALD, S. STERN) 14 October 2010 See paragraphs [0020]-[0057]; and figures 1-4.	1-23

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 January 2014 (17.01.2014)	**20 January 2014 (20.01.2014)**

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