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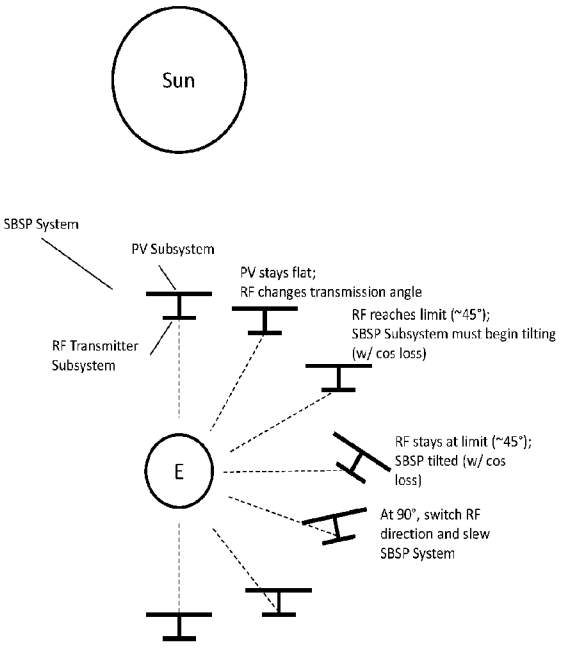


FIG. 1B

(57) Abstract: Systems and methods in accordance with various embodiments of the invention implement mirrors that are more transparent to specific regions of the electromagnetic spectrum (e.g. the microwave region of the electromagnetic spectrum) relative to conventional metallic mirrors (e.g. mirrors made form aluminum or silver). In one embodiment, a space-based solar power system includes: a photovoltaic material; and a mirror that is - relative to a 10 μm thick sheet of aluminum - more transparent to at least one of a substantial portion of the microwave region of the electromagnetic spectrum and a substantial portion of the radio wave region of the electromagnetic spectrum; where the mirror is configured to focus incident visible light onto the photovoltaic material.

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MIRRORS TRANSPARENT TO SPECIFIC REGIONS OF THE ELECTROMAGNETIC SPECTRUM

FIELD OF THE INVENTION

[0001] The present invention is related to mirrors that are transparent to specific regions of the electromagnetic spectrum, and their implementation in Space-based Solar Power (SBSP) Systems.

BACKGROUND

[0002] Space-based Solar Power (SBSP) describes the collection of solar power in space by a Solar-Power Satellite or a Satellite Power System (SPS) and then the conversion and transmission of the power to a remote receiver for conversion back to electrical power. In an SBSP System, solar energy is collected as electrical energy on board, powering some manner of wireless power transmission to a receiver located remotely from the SBSP System. The wireless power transmission application might include a microwave transmitter or laser emitter, which would direct its beam toward a collector, such as a power receiving rectenna at the remote location, such as, on the Earth's surface.

[0003] SBSP differs from ground-based solar collection methods in that the means used to collect energy resides on an orbiting satellite instead of on the Earth's surface. Basing such a system in space results in a higher collection rate for the solar energy due to the lack of a diffusing atmosphere. In a conventional ground-based system a large percentage (55-60%) of the solar energy is lost on its way through the atmosphere by the effects of reflection and absorption. Space-based solar power systems convert solar energy to a far-field emission such as microwaves outside the atmosphere, avoiding these losses. In addition, SBSP Systems have a longer collection period and the ability to collect solar energy continuously without the downtime (and cosine losses, for fixed flat-plate collectors) that result from the Earth's rotation away from the sun.

[0004] A general limitation for conventional SBSP Systems is the size of SPS required to generate sufficient electrical power from solar energy. For example, for a 500 MW system a 5 km^2 platform may be required. Such a platform would conventionally be formed of large satellites on the order of tens to hundreds of tonnes/satellite. The launch costs associated with placing such large structures into orbit reduces the economic viability of conventional SBSP Systems.

SUMMARY OF THE INVENTION

[0005] Systems and methods in accordance with various embodiments of the invention implement mirrors that are more transparent to specific regions of the electromagnetic spectrum (e.g. the microwave region of the electromagnetic spectrum) relative to conventional metallic mirrors (e.g. mirrors made form aluminum or silver). In one embodiment, a space-based solar power system includes: a photovoltaic material; and a mirror that is – relative to a 10 μm thick sheet of aluminum – more transparent to at least one of a substantial portion of the microwave region of the electromagnetic spectrum and a substantial portion of the radio wave region of the electromagnetic spectrum; where the mirror is configured to focus incident visible light onto the photovoltaic material.

[0006] In another embodiment, the mirror includes alternating layers of high refraction index materials and low refraction index materials.

[0007] In yet another embodiment, the alternating layers of high refraction index and low refraction index materials are disposed on a polymer membrane.

[0008] In still another embodiment, a plurality of the high refraction index materials include the same material, and a plurality of the low refraction index materials include the same material.

[0009] In still yet another embodiment, the alternating layers of high refraction index and low refraction index materials are configured such that incident light reflects off of the constituent interfaces and thereby constructively interferes to achieve reflection.

[0010] In a further embodiment, adjacent high refraction index and low refraction index materials define a pair, and the mirror includes at least 72 pairs.

[0011] In a still further embodiment, adjacent high refraction index and low refraction index materials define a pair, and the mirror includes at least 144 pairs.

[0012] In a yet further embodiment, adjacent high refraction index and low refraction index materials define a pair, and at least two of the pairs include different materials.

[0013] In a still yet further embodiment, the different pairs each give rise to different reflectivity profiles.

[0014] In another embodiment, at least two reflectivity profiles are characterized by a reflectance % of greater than 90% for at least some region within the visible light portion of the electromagnetic spectrum.

[0015] In still another embodiment, at least one layer that includes a low index refraction material includes one of: MgF_2 and SiO_2.

[0016] In yet another embodiment, at least one layer that includes a high index refraction material includes one of: Diamond, AlN, and Ta_2O_5.

[0017] In still yet another embodiment, adjacent high refraction index and low refraction index materials define a pair, and at least one pair includes Diamond and MgF_2 adjacently disposed.

[0018] In a further embodiment, adjacent high refraction index and low refraction index materials define a pair, the mirror includes at least 72 pairs, and each of the pairs includes Diamond and MgF_2 adjacently disposed.

[0019] In a still further embodiment, adjacent high refraction index and low refraction index materials define a pair, the mirror includes at least 144 pairs, and each of the pairs includes Diamond and MgF_2 adjacently disposed.

[0020] In a yet further embodiment, the thickness of the mirror is between approximately 1 μm and approximately 10 μm.

[0021] In a still yet further embodiment, adjacent high refraction index and low refraction index materials define a pair, and at least one pair includes AlN and SiO_2 adjacently disposed.

[0022] In another embodiment, adjacent high refraction index and low refraction index materials define a pair, and at least one pair includes Diamond and SiO_2 adjacently disposed.

[0023] In still another embodiment, adjacent high refraction index and low refraction index materials define a pair, and at least one pair includes AlN and MgF_2 adjacently disposed.

[0024] In yet another embodiment, adjacent high refraction index and low refraction index materials define a pair, and at least one pair includes Ta_2O_5 and MgF_2 adjacently disposed.

[0025] The features and advantages described in the specification are not all inclusive and, in particular, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the drawings, specification, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The description will be more fully understood with reference to the following figures and data graphs, which are presented as various embodiments of the disclosure and should not be construed as a complete recitation of the scope of the disclosure, wherein:

[0027] FIG. 1A illustrates the operation of a SBSP System that relies on a conventional, metallic mirror for operation.

[0028] Figure 1B illustrates the operation of a SBSP System that incorporates a mirror that is substantially transparent to a specified region of the electromagnetic spectrum in accordance with many embodiments of the invention.

[0029] FIG. 1C illustrates a comparison of the relative performance of a SBSP System that incorporates a conventional, metallic mirror and a SBSP system that incorporates a mirror that is relatively transparent to a targeted region of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0030] FIGS. 2A-2B illustrate how the reflectance of a mirror that is substantially transparent to predetermined regions of the electromagnetic spectrum can increase with an increasing number of constituent pairs of films characterized by alternating high and low refraction indices in accordance with certain embodiments of the invention.

[0031] FIG. 3 illustrates how the reflectance profile of a mirror that is substantially transparent to targeted regions of the electromagnetic spectrum can vary based on the

number of constituent pairs of materials in accordance with certain embodiments of the invention.

[0032] FIGS. 4A-4C illustrate the average reflectivity values for various mirrors that can be implemented in accordance with many embodiments of the invention.

[0033] FIGS. 5A-5B illustrate the mass per area and the specific power for SBSP Systems that incorporate conventional metallic mirrors relative to SBSP Systems that incorporate mirrors in accordance with certain embodiments of the invention.

[0034] FIG. 6 illustrates the specific energy per orbit of SBSP Systems that incorporate conventional metallic mirrors relative to SBSP Systems that incorporate mirrors in accordance with certain embodiments of the invention.

[0035] Figure 7 conceptually illustrates a large-scale space-based solar power station with a plurality of power satellite modules in geosynchronous orbit about the Earth, which can benefit from the incorporation mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0036] Figure 8 conceptually illustrates a large-scale space-based solar power station with a plurality of power satellite modules flying in a rectangular orbital formation, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0037] Figure 9 conceptually illustrates a large-scale space-based solar power station, a satellite module, and a cross-sectional view of a modular power generation tile, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0038] Figure 10a conceptually illustrates a cross-sectional view of a modular power generation tile, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0039] Figure 10b conceptually illustrates a cross-sectional view of a photovoltaic cell, which can benefit from an association with mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0040] Figure 10c conceptually illustrates a block-diagram for an integrated circuit suitable for utilization in a power transmitter forming part of a power generation tile, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0041] Figure 11 conceptually illustrates an array of power generation tiles in which the antenna elements of the power generation tiles are configured as a phased array, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0042] Figure 12 conceptually illustrates the power density distribution at a ground receiver from a transmission of power from a phased array of antennas on a solar power station, which can benefit from an association with mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0043] Figure 13 conceptually illustrates dynamic power allocation from a large-scale space-based solar power system, which can benefit from an association with mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0044] Figures 14a and 14b conceptually illustrate electronic beam steering using relative phase offset between elements of a phased array within the context of a space-based solar power station that can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0045] Figure 15a conceptually illustrates a large-scale space-based solar power station and a compactable satellite module in a deployed configuration, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0046] Figure 15b conceptually illustrates a retracted compactable satellite module, according to Figure 15a in a retracted configuration, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0047] Figure 16 conceptually illustrates a compactable satellite module having a biaxial folding configuration, which can benefit from mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0048] Figure 17 provides images of the compaction of a membrane using the compaction technique of Figure 16.

[0049] Figures 18a to 18d conceptually illustrate a cross-sectional view of a compactable satellite module having a slip folding and wrapping configuration, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0050] Figure 19 conceptually illustrates a perspective view of a compactable satellite module having a slip folding and wrapping configuration, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0051] Figure 20 provides images of the compaction of a membrane using the compaction technique of Figure 19.

[0052] Figure 21 conceptually illustrates a boom deployment mechanism for a compactable satellite module, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0053] Figure 22 conceptually illustrates a spin deployment mechanism for a compactable satellite module, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0054] Figures 23A-23B illustrate data pertaining to an ALTADEVICES photovoltaic material that can be incorporated in a space-based solar power station, which can benefit from an association with mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0055] Figure 24 illustrates a cross section of a portion of a PV cell that can be incorporated in a space-based solar power station, which can benefit from an association with mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0056] Figure 25 depicts an illustrative energy balance for an ALTADEVICES DUAL Junction Cell that can be incorporated in a space-based solar power station, which can benefit from an association with mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0057] Figures 26A-26C illustrate a Cassegrain configuration that can be implemented in a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0058] Figure 27 illustrates the operation of a Parabolic Trough configuration that can be implemented in a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0059] Figures 28A-28B illustrate a Venetian Blinds configuration that can be incorporated in a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0060] Figure 29A illustrates the constitution of a Venetian Blinds configuration in a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with an embodiment of the invention.

[0061] Figure 29B illustrates a Venetian Blinds configuration coupled with a power transmitter adapted for use in a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with an embodiment of the invention.

[0062] Figure 30 illustrates how the mass of a power generation tile can be significantly reduced by implementing concentrators within the context of a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0063] Figure 31 illustrates how the efficiency of a power generation tile can be a stronger function of the number of junctions implemented relative to the concentration implemented.

[0064] Figures 32A-32B illustrate using a conductive carbon spring and a conductive reflector as the metallic contacts for a photovoltaic material in the context of a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0065] Figures 33A-33C illustrate using a reflector as the contacts for a photovoltaic material in the context of a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0066] Figure 34 illustrates using carbon springs as the contacts for a photovoltaic material in the context of a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

[0067] Figure 35 illustrates photovoltaic materials electrically connected in parallel in the context of a space-based solar power station, which can benefit from the incorporation of mirrors that are substantially transparent to certain regions of the electromagnetic spectrum in accordance with certain embodiments of the invention.

DETAILED DESCRIPTION

[0068] Turning now to the drawings, mirrors that are more transparent to predetermined regions of the electromagnetic spectrum relative to conventional mirrors (e.g. those fabricated from aluminum or silver) in accordance with many embodiments of the invention are illustrated. Many systems, including many systems configured for extraterrestrial operation, can benefit from such structures. For example, many SBSP Systems implement concentrators, e.g. in the form of mirrors, to focus solar radiation onto constituent photovoltaic materials, which then generate electrical current based on the incident solar radiation. As can be appreciated, a photovoltaic material's ability to generate electrical current is related to the amount of incident solar radiation / flux. For instance, U.S. Pat. App. No. 14/728,985, entitled "Large-Scale Space-Based Solar Power Station: Efficient Power Generation Tiles," discloses SBSP Systems that incorporate mirrors to focus solar radiation onto constituent photovoltaic materials, and the respective generation of electrical current. U.S. Pat. App. No. 14/728,985 is hereby incorporated by reference in its entirety, especially as it pertains to the disclosure of SBSP Systems that incorporate mirrors to focus solar radiation onto photovoltaic materials. As explained in U.S. Pat. App. No. 14/728,985, using concentrators to increase the solar flux experienced by a photovoltaic material can be advantageous relative to simply increasing the surface area of a photovoltaic material to increase electric current generation in a number of respects. For example, configurations that utilize concentrators in the aforementioned manner can be less massive than those that implement relatively more photovoltaic material (e.g. as measured by surface area). This is because photovoltaic materials are typically implemented in conjunction with cover glass, which can be relatively massive. Hence, the more photovoltaic material that is used, the more – relatively massive – attendant cover glass is used (generally

speaking). As can be appreciated, it is often desirable to implement SBSP Systems having a reduced payload, e.g. to reduce launch costs and to improve maneuverability. SBSP Systems that utilize concentrators, e.g. in the form of mirrors, can be advantageous insofar as they can provide for greater power generation per unit mass.

[0069] While the implementation of mirrors in this manner can enable improved efficacy and efficiency for SBSP Systems, the utilization of conventional metallic mirrors, such as aluminum films or silver surfaces, can introduce some problems. For example, such metallic mirrors can interfere with the wireless transmission of the generated power. FIG. 1A illustrates how metallic mirrors used in SBSP Systems can interfere with the wireless transmission of generated power. In particular, FIG. 1A illustrates the operation of a SBSP System that incorporates a conventional metallic mirror to focus solar radiation on constituent photovoltaic material. More specifically, it is illustrated that the SBSP System includes a Photovoltaic (PV) Subsystem to generate power and a Radiofrequency (RF) Transmitter Subsystem to wirelessly transmit the generated power. FIG. 1A depicts the SBSP System in various positions as it orbits around the Earth. For the purposes of this discussion, the position of the SBSP System will be referenced using 'clock position' relative to the Earth. For example, at the 12 o'clock position, the SBSP System is directly between the Earth and the Sun. At this position, the PV subsystem experiences the greatest solar flux. At the ~1 o'clock position, it is depicted that the RF Subsystem has to wirelessly transmit the generated power at an angle. Notably, the RF System must maintain at least a ~45° angle relative to the Earth in order to properly wirelessly transmit power. Accordingly, it is depicted that, at the ~1:30 position, the SBSP System must begin tilting in order to accommodate the requirement that the RF Subsystem maintain at least a ~45° angle relative to the Earth. This tilting results in further 'cosine losses'; 'cosine losses' refer to the loss in efficacy/efficiency of solar power generation when the photovoltaic material is not directly orthogonal to the incident sunrays. At the 3 o'clock position, the SBSP System is depicted as tilted to maintain the threshold minimum angular positional relationship with respect to the Earth. At the ~4 o'clock position, the SBSP System is depicted as continuing its tilting in the same rotational direction as it orbits the Earth so as to

maintain power transmission. The SBSP System continues to tilt in this manner as it orbits the Earth and eventually reaches a point where the photovoltaic material within the PV Subsystem does not experience sufficient incident solar radiation to result in significant power generation; this phenomenon occurs for a substantial portion of the SBSP System's orbit. In FIG. 1A, this phenomenon is depicted as occurring between approximately the ~5 o'clock position and the ~7 o'clock position. The spatial region within which the SBSP System does not generate and transmit significant power is known as the 'Dark Region.'

[0070] Importantly, conventionally implemented metallic mirrors (e.g. made from aluminum or silver) are typically not transparent to RF electromagnetic waves. Rather, such metallic materials can substantially interfere with the transmission of RF waves. As a result, the RF Subsystem cannot simply wirelessly transmit power through the PV Subsystem. Thus, many embodiments of the invention are directed to implementing mirrors that are much more transparent to targeted portions of the electromagnetic spectrum, e.g. the RF region. This can allow for a more flexible operation for a respective SBSP System. For example, FIG. 1B illustrates the operation of a SBSP System that incorporates mirrors that are configured to focus solar radiation onto constituent photovoltaic materials and that are more transparent to the radiofrequency portion of the electromagnetic spectrum relative to conventional mirrors. In particular, the FIG. 1B is similar to FIG. 1A insofar as it depicts the operation of a SBSP System that includes a PV Subsystem and a RF Transmitter Subsystem. Additionally, as before, the SBSP System must tilt to accommodate the minimum orientation angle required by the RF Transmitter Subsystem to maintain proper wireless power transmission. However, unlike the SBSP System depicted in FIG. 1A, the SBSP System depicted in FIG 1B includes mirrors that are transparent to the RF electromagnetic waves used to transmit the generated power. As a result, the SBSP System can tilt in a manner so that the reception of incident solar radiation is maintained for substantially the entire orbit. In other words, there is no significant Dark Region. Thus, FIG. 1B illustrates that at the 3 o'clock position, the SBSP System 'slews' and switches the direction of the RF transmission. Because the mirror (along with the remainder of the PV Subsystem) is

more transparent to the RF portion of the electromagnetic spectrum, the transmission can pass through the PV Subsystem to a greater extent than it could for conventionally implemented PV subsystems. In this way, the SBSP System can maintain power generation and transmission for virtually its entire orbit.

[0071] FIG. 1C illustrates the increase in relative performance that can result for a SBSP System that utilizes the disclosed mirrors to focus solar radiation onto associated photovoltaic material in accordance with certain embodiments of the invention in comparison with SBSP Systems that utilize conventional metallic mirrors to do so. In particular, it is illustrated that the relative performance of the two systems largely coincide between approximately the ~9 o'clock position and the ~3 o'clock position (with respect to a clockwise direction). However, between the ~3 o'clock position and the ~9 o'clock position, the relative performance of the SBSP System that utilizes conventional metallic mirrors – indicated by the line including the filled circles and labeled "Opaque to RF – tends to zero (coinciding with the Dark Region), while the relative performance of the SBSP System that utilizes mirrors more transparent to the RF region of the electromagnetic spectrum – indicated by the line without the filled circles and labeled "Transparent to RF" – can maintain significant power generation and transmission for virtually its entire orbit. It is illustrated that the performance of the SBSP System that includes the disclosed mirrors can drop to zero briefly while the SBSP System 'slews' and correspondingly reverses the RF transmission direction. In general, the implementation of the disclosed mirrors can allow for the collocation of optical collection elements and electromagnetic transmissive elements while mitigating obstruction issues.

[0072] Mirrors that are more transparent to specified regions of the electromagnetic spectrum, and their incorporation in SBSP Systems, are now discussed in greater detail below.

MIRRORS THAT ARE TRANSPARENT TO SPECIFIED REGIONS OF THE ELECTROMAGNETIC SPECTRUM

[0073] In many embodiments of the invention, mirrors are implemented that are relatively more transparent to predetermined portions of the electromagnetic spectrum as compared to conventional mirrors (e.g. made from aluminum or silver). In a number of embodiments, the mirrors are configured such that they are optically reflective, but are more transparent to at least certain of those portions of the electromagnetic spectrum that are commonly used for wireless power transmission (e.g. the microwave region and the radio wave region). In many embodiments, the mirrors are more transparent to at least a substantial portion (e.g. the majority of) of one of the microwave region and the radio wave region. In numerous embodiments, the mirrors are more transparent in one of the following ranges: between approximately 300 GHz and approximately 30 GHz; between approximately 30 GHz and approximately 3 GHz; between approximately 3 GHz and approximately 300 MHz; between approximately 300 MHz and approximately 30 MHz; between approximately 30 MHz and approximately 3 MHz; between approximately 3 MHz and approximately 300 kHz; between approximately 300 kHz and approximately 30 kHz; between approximately 30 kHz and approximately 3 kHz; and portions and combinations thereof. In this way, the mirrors can be implemented in SBSP Systems such as those described above, so as to allow for power generation and transmission for virtually the entire orbit.

[0074] In many embodiments the mirrors take the form of alternating layers of high and low refraction index materials; the reflective characteristic of the mirror can be achieved via constructive interference. Note that in many instances, the reflectance of the mirror can be a function of the number of pairs of high and low refraction index materials implemented. In many instances, the alternating layers are disposed on a polymer membrane. As an example, FIGS. 2A-2B illustrate the structure of a mirror characterized by pairs of high and low refraction index materials, and how the reflectance of such a mirror can increase with the number of constituent pairs, in accordance with certain embodiments of the invention. In particular, FIG. 2A illustrates the structure of a mirror characterized by pairs of high and low refraction index

materials. More specifically, it is depicted that relatively high and low refraction index materials are adjacently disposed, and define one pair. Incident light reflects that the respective interfaces, and thereby constructively interferes to achieve reflection. FIG. 2B illustrates that the reflectance of such a configuration can be a function of the number of implemented pairs. Accordingly, in many embodiments, a mirror is characterized by a relatively high number of pairs of constituent layers.

[0075] In many instances, the number of pairs of constituent layers can impact the reflectance profile (relative to wavelength) of the mirror. For instance, FIG. 3 illustrates the reflectance profile (relative to wavelength) for a mirror characterized by 10 pairs of high-low refraction index materials, a mirror characterized by 18 pairs of such materials, and a mirror characterized by 27 pairs of such materials. More specifically, the illustrated graph is with respect to a mirror having pairs of layers of AlAs (Aluminum Arsenide) and GaAs (Gallium Arsenide). In effect, it is seen that each configuration reflects different wavelengths differently. In many instances, it is desirable to have a mirror characterized by a high reflectivity with respect to an entire region of the electromagnetic spectrum, e.g. the visible portion of the electromagnetic spectrum (for example, as opposed to having high reflectivity with respect to only certain portions of a region). Thus, in many embodiments, such different pairing configurations can be multiplexed to realize a mirror having a more broadband reflectivity profile. In many embodiments, configurations are implemented such that the reflectance percentage is greater than 90% for a substantial portion of a spectral band (e.g. the visible portion of the electromagnetic spectrum). In many embodiments, the reflectance percentage is greater than 80% for a majority of the visible portion of the electromagnetic spectrum. Of course, although FIG. 3 depicts the various configurations centered on that portion of the electromagnetic spectrum corresponding with a wavelength of 1064 nm, different material combinations can be implemented to center the reflectivity around any suitable desired region of the electromagnetic spectrum, e.g. the visible region of the electromagnetic spectrum, in accordance with many embodiments of the invention. Moreover, while specific threshold percentages are mentioned, it should be clear that

any suitable reflectivity profile(s) can be implemented in accordance with numerous embodiments of the invention.

[0076] Notably, while conventional materials – such as those based entirely on TiO_2 and/or SiO_2 – may be sufficient to provide a reflective surface, they might have characteristics that would hinder their performance as concentrators in in SBSP Systems. For example, in many SBSP systems, such as those described in U.S. Pat. App. No. 14/728,985, incorporated by reference above, the concentrators also serve as 'fins' insofar as they help radiate heat away from the structures, and thereby facilitate the maintenance of suitable operating temperatures. Conventional reflective surfaces may not have optimal thermal conductivity characteristics. Accordingly, in many embodiments, material combinations are implemented that have favorable thermal conductivity characteristics (e.g. high thermal conductivities). For example, in numerous embodiments, the mirror is constructed from combinations of: AlN, Diamond, and/or Ta_2O_5, MgF_2, SiO_2.

[0077] Furthermore, in many instances it can be desirable to implement mirrors that are characterized by relatively light weights. For instance, as alluded to previously, it is often desirable to reduce the overall payload for SBSP Systems; reducing the weight can provide for reduced launch costs and greater maneuverability in orbit. Table 1 below lists sample weight values for various combinations of alternating materials that can be implemented in accordance with embodiments of the invention. In particular, Table 1 lists mass per unit area values for 72 layer configurations and 144 layer configurations for each of the listed material combinations. Any of the configurations listed in Table 1 can be implemented to construct mirrors in accordance with embodiments of the invention.

Table 1: Material Weight

Material combination	72 layers (g/m^2)	144 layers (g/m^2)
Diamond/MgF_2	26.3	52.7
Diamond/SiO_2	23.3	46.5
AlN/MgF_2	26.4	52.8
AlN/SiO_2	23.3	46.5
Ta_2O_5/MgF_2	46.9	93.7
Ta_2O_5/SiO_2	42.8	85.7

[0078] Notably, the reflectivity of the mirror can be dependent on the respective angle of incidence, and this dependency can be a function of specific material combinations. Hence, in many embodiments, particular materials combinations are implemented that result in mirrors characterized by reflectivity profiles that are relatively resilient against incident angle variation. For example, FIGS. 4A-4C illustrate reflectivity values as a function of incident angle for different material combinations that can form mirrors in accordance with many embodiments of the invention. In particular, data for various combinations of high refraction index materials and low refraction index materials are depicted. Specifically, the constituent high refraction index materials are one of: Diamond, AlN, and Ta_2O_5; and the constituent low refraction index material are one of: MgF_2 and SiO_2. More specifically, FIG. 4A illustrates data for mirror configurations that include 72 layers of material, and FIG. 4B illustrates data for mirror configurations that include 144 layers of material. FIG. 4C illustrates data for particular mirror configurations. Note that it is illustrated that the material combinations involving diamond can generally demonstrate greater reflectivity over a broader incident angle range. It is further illustrated that the combinations involving MgF_2 as the low refraction index material generally have higher average reflectivity values than those that implement SiO_2 as the low refraction index material. It can also be seen that mirror configurations implementing more layers generally demonstrate higher reflectivity values. However, as mentioned above, a countervailing consideration for the implementation of more layers can be that the implementation of more layers generally increases the mass of the structure, which can be undesirable in several circumstances. Nevertheless, to be clear any of the mirror configurations illustrated in FIGS. 4A-4C can be implemented in accordance with many embodiments of the invention.

[0079] As can be appreciated, the overall optical efficiency of the mirror is also an important consideration. Table 2 lists sample optical efficiencies for the listed mirror configurations and conventional mirrors.

Table 2: Optical Efficiencies for mirror combinations

Reflector	Optical Efficiency
AlN/SiO_2 72 layers	91.4
AlN/SiO_2 144 layers	97.6
Silver experimental	86.5
Silver literature	91.8
Perfect mirror	98.6

In many embodiments, mirrors are implemented that include constituent materials that allow the mirror to have relatively high optical efficiency values.

[0080] FIGS. 5A-5B illustrate the performance characteristics of AlN/SiO_2 mirror configurations relative to a conventional 10 μm thick aluminum mirror within the context of an SBSP System where concentrators are used to focus solar radiation onto constituent photovoltaic materials. As mentioned previously, for a given power generation value, the utilization of greater concentration can enable the implementation of less massive SBSP systems. FIG. 5A illustrates how the reduction in mass is similar for each of a 72 layer AlN/SiO_2 mirror configuration, a 144 layer AlN/SiO_2 mirror configuration, and a 10 μm thick aluminum mirror. Relatedly, FIG. 5B illustrates how the specific power – power per unit mass – similarly increases with the utilization of greater concentration as between a 72 layer AlN/SiO_2 mirror configuration, a 144 AlN/SiO_2 mirror configuration, and a 10 μm thick aluminum mirror.

[0081] FIG. 6 illustrates how the implementation of a mirror that is transparent to specified regions of the electromagnetic spectrum can provide for vastly improved power generation characteristics when implemented within an SBSP System, relative to a conventional mirrored surface. In particular, the specific energy per orbit for SBSP Systems that utilize AlN/SiO_2 mirror configurations is depicted relative to SBSP Systems that utilize conventional mirrors. As can be seen, utilizing the disclosed mirror configurations can enable vastly superior power generation metrics within the context of an SBSP System.

[0082] Note that while the above data has in part regarded 72 layer and 144 layer mirror configurations, mirrors having any suitable number of constituent layers can be implemented in accordance with many embodiments of the invention. Embodiments of the invention are not limited to specific numbers of constituent layers.

[0083] Importantly, while examples of suitable combinations of high refraction index and low refraction index materials have been given, it should be clear that any of a variety of suitable such combinations can be implemented in accordance with many embodiments of the invention. More generally, any suitable structure that can function as a mirror, but that is relatively more transparent (as compared to conventional mirrors such as a 10 μm sheet of Aluminum or a 10 μm sheet of silver) to at least some portion of the radio wave portion of the electromagnetic spectrum or the microwave portion of the electromagnetic spectrum, can be implemented in accordance with embodiments of the invention.

[0084] Note that any suitable techniques can be used to fabricate the above-described mirrors. For instance, in many embodiments, sputtering techniques are used to deposit the constituent layers of the described mirrors. For instance, SiO_2, MgF_2, AlN, and Ta_2O_5, may be amenable to sputtering deposition. In many instances, chemical vapor deposition can be used to deposit the constituent layers. For instance, the deposition of diamond may be amenable to chemical vapor deposition techniques. To be clear, the described mirrors can be fabricated using any suitable techniques in accordance with embodiments of the invention, including any suitable deposition techniques. Additionally, the described mirrors can be manufactured to conform to any suitable thickness in accordance with many embodiments of the invention. In many embodiments, the thickness of the mirror is based on the specific requirements of the context that it is to be implemented in. For example, in many embodiments, the thickness of the mirror is between approximately 1 μm and approximately 10 μm. In a number of embodiments where the mirror is to be used in an SBSP System, the thickness of the implemented mirror is approximately 2.5 μm. Additionally, the particular regions of the electromagnetic spectrum that the implemented mirrors are transparent to can be based on the structure of the mirror. Accordingly, in many instances, structures

are implemented that enable the mirror to be transparent to predetermined targeted regions of the electromagnetic spectrum. In many instances, configurations are implemented that allow the mirror to be transparent to that region of the electromagnetic spectrum conventionally used to wirelessly transmit power (e.g. the microwave region and/or the radio wave region). Of course, mirrors can be made to be transparent to any appropriate region of the electromagnetic spectrum in accordance with embodiments of the invention.

[0085] While the mirrors described above have largely been presented in the context of SBSP Systems, such as those described in U.S. Pat. App. No. 14/728,985, it should be clear that the described mirrors can be implemented in conjunction with any of a variety of structures, including any of a variety of SBSP Systems. For example, the disclosed structures can be used in conjunction with the systems and methods described in: U.S. provisional patent application serial number 61/993,016 entitled "Large-Scale Space-Based Array: Packaging, Deployment and Stabilization of Lightweight Structures," filed on May 14, 2014; U.S. provisional patent application serial number 61/993,025 entitled "Large-Scale Space-Based Array: Multi-Scale Modular Space Power System," filed on May 14, 2014; U.S. provisional patent application serial number 61/993,957 entitled "Large-Scale Space-Based Array: Modular Phased Array Power Transmission," filed May 15, 2014; U.S. provisional patent application serial number 61/993,037 entitled "Large-Scale Space-Based Array: Space-Based Dynamic Power Distribution System," filed May 14, 2014; U.S. provisional patent application serial number 62/006,604 entitled "Large-Scale Space-Based Array: Efficient Photovoltaic Structures for Space," filed June 2, 2014; U.S. provisional patent application serial number 62/120,650 entitled "Large-Scale Space-Based Array: Packaging, Deployment and Stabilization of Lightweight Structures," filed February 25, 2015; U.S. patent application serial number 14/712,812 entitled "Large-Scale Space-Based Solar Power Station: Packaging, Deployment and Stabilization of Lightweight Structures," filed May 14, 2015; U.S. patent application serial number 14/712,783 entitled "Large-Scale Space-Based Solar Power Station: Multi-Scale Modular Space Power," filed May 14, 2015; U.S. patent application serial number 14/712,856 entitled

"Large-Scale Space-Based Solar Power Station: Power transmission Using Steerable Beams," filed May 14, 2015; and U.S. patent application serial number 14/728,985 entitled "Large-Scale Space-Based Solar Power Station: Efficient Generation Tiles," filed June 2, 2015, all of which are incorporated by reference herein in their entirety.

[0086] To be clear, although the implementation of the mirrors that are relatively more transparent to specified regions of the electromagnetic spectrum have been discussed above largely in the context of SBSP Systems, it should be clear that the described mirrors can be implemented on any of a variety of structures, including any of a variety of structures configured for extraterrestrial operation, in accordance with many embodiments of the invention. For instance, they can be implemented in any of a variety of structures, where it may be beneficial to be able to transmit electromagnetic signals through the structure. Nevertheless, suitable space-based solar power generation apparatus that can benefit from the described mirrors are described below.

Suitable Space-based Solar Power Stations that can Benefit from the described Mirrors

[0087] A large-scale space-based solar power station that can benefit from the incorporation mirrors that are more transparent to specified regions of the electromagnetic spectrum in accordance with many embodiments can be a modular space-based construct that can be formed from a plurality of independent satellite modules placed into orbit within an orbital formation such that the position of each satellite module relative to each other is known. Each of the satellite modules can include a plurality of power generation tiles that capture solar radiation as electrical current and use the current to transmit the energy to one or more remote receivers using power transmitters. In many instances, the transmissions are generated using microwave power transmitters that are coordinated to act as a phased- and/or amplitude array capable of generating a steerable beam and/or focused beam that can be directed toward one or more remote receivers. In other instances, any of a variety of appropriate power transmission technologies can be utilized including (but not limited to) optical transmitters such as lasers.

[0088] In many instances, lightweight space structures used to construct the modular elements of the solar power station can benefit from the incorporation of the described mirrors. Some such lightweight space structures are used in the construction of the power generation tiles and/or satellite modules and may incorporate movable elements that allow the lightweight space structure to be compacted prior to deployment to reduce the area or dimensional length, height and/or width of the power generation tiles and/or satellite modules prior to deployment. The space structures may be made of any number, size and configuration of movable elements, and the elements may be configured to compact according to any suitable compacting mechanism or configuration, including one or two-dimensional compacting using, among others, z-folding, wrapping, rolling, fan-folding, double z-folding, Miura-ori, slip folding, wrapping, and combinations thereof. Some such movable elements are interrelated by hinges, such as, frictionless, latchable, ligament, and slippage hinges, among others. Some structures are pre-stressed and/or provided with supportive frameworks to reduce out-of-plane macro- and micro-deformation of the lightweight structures. Structures and modules may include dynamic stabilizing movement (e.g., spinning) during deployment and/or operation. Deployment mechanisms to deploy the compactible lightweight structures into a deployed operational state may be incorporated into or associated with instances of the lightweight structures. Some deployment mechanisms may include (but are not limited to) expansive boom arms, centrifugal force mechanisms such as tip masses or module self-mass, among others.

[0089] Large-scale space-based solar power stations that can benefit from the described mirrors according to many embodiments can utilize a distributed approach to capture solar radiation, and use the energy thus captured to operate power transmitters, which transmit power to one or more remote receivers (e.g., using laser or microwave emissions). The satellite modules of the solar power station can be physically independent structures, each comprising an independent array of power generation tiles. The satellite modules can each be placed into a specified flying formation within an array of such satellite modules in a suitable orbit about the Earth. The position of each of the independent satellite modules in space within the orbital array formation can

be controllable via a combination of station-keeping thrusters and controlled forces from absorption, reflection, and emission of electromagnetic radiation, as well as guidance controls. Using such controllers, each of the independent satellite modules may be positioned and maintained within the controlled orbital array formation relative to each of the other satellite modules so that each satellite module forms an independent modular element of the large-scale space-based solar power station. The solar radiation received by each of the power generation tiles of each of the independent satellite module can be utilized to generate electricity, which can power one or more power transmitters on each of the power generation tiles. Collectively, the power transmitters on each of the power generation tiles can be configured as independent elements of a phased and/or amplitude-array.

[0090] The power generation tiles and/or satellite modules may also include separate electronics to process and exchange timing and control information with other power generation tiles and/or satellite modules within the large-scale space-based solar power station. In many implementations, the separate electronics form part of an integrated circuit that possesses the ability to independently determine a phase offset to apply to a reference signal based upon the position of an individual tile and/or transmitter element. In this way, coordination of a phased array of antennas can be achieved in a distributed manner.

[0091] In some instances of the distributive approach, different array elements of the phased array may be directed to transmit power with different transmission characteristics (e.g., phase) to one or more different remote power receiving collectors (e.g., ground based rectenna). Each satellite module of power generation tiles, or combinations of power generating tiles across one or more satellite modules, may thus be controlled to transmit energy to a different power receiving collector using the independent control circuitry and associated power transmitters.

[0092] A photovoltaic cell (PV) refers to an individual solar power collecting element on a power generation tile in a satellite module. The PV includes any electrical device that converts the energy of light directly into electricity by the photovoltaic effect including elements made from polysilicon and monocrystalline silicon, thin film solar cells that include amorphous silicon, CdTe and CIGS cells, multijunction cells, perovskite cells, organic/polymer cells, and various alternatives thereof.

[0093] A power transmitter or radiator refers to an individual radiative element on a power generation tile in a satellite module and its associated control circuitry. A power transmitter can include any device capable of converting power in the electrical current generated by the PV to a wireless signal, such as microwave radiation or light, including (but not limited to) a laser, a klystron, a traveling-wave tube, a gyrotron, or suitable transistor and/or diode. A power transmitter may also include suitable transmissive antennas, such as, dipole, patch, helical or spherical antennas, among others.

[0094] A phased array refers to an array of power transmitters in which the relative phases of the respective signals feeding the power transmitters are configured such that the effective radiation pattern of the power emission of the array is reinforced in a desired emission direction and suppressed in undesired directions. Phased arrays may be dynamic or fixed, active or passive.

[0095] An orbital array formation refers to any size, number or configuration of independent satellite modules being flown in formation at a desired orbit in space such that the position of the satellite modules relative to each other is known such that power generation tiles on each of the satellite modules within the formation serves as an array element in the phased array of the solar power station.

[0096] A power generation tile refers to an individual solar power collecting and transmitting element in the phased array of the large-scale space-based solar power station. In many instances a power generation tile is a modular solar radiation collector, converter and transmitter that collects solar radiation through at least one photovoltaic cell disposed on the tile, and uses the electrical current to provide power to at least one power transmitter collocated on the same tile that transmits the converted power to one or more remote power receiving collectors. Many of the power generation tiles

incorporated within a space-based solar power station include separate control electronics independently control the operation of the at least one power transmitter located on the power generation tile based upon timing, position, and/or control information that may be received from other tiles and/or other modules within the large-scale space-based solar power station. In this way, the separate control electronics can coordinate (in a distributed manner) the transmission characteristics of each of the power generation tiles form a phased array. Each power generation tile may also include other structures such as radiation collectors for focusing solar radiation on the photovoltaic, thermal radiators for regulating the temperature of the power generation tile, and radiation shielding, among other structures.

[0097] A satellite module refers to an array of power generation tiles collocated on a single integral space structure. The space structure of the satellite module may be a compactable structure such that the area occupied by the structure may be expanded or contracted depending on the configuration assumed. The satellite modules may include two or more power generation tiles. Each power generation tile may include at least one solar radiation collector and power transmitter. As discussed above, each of the power generation tiles may transmit power and may be independently controlled to form an array element of one or more phased arrays formed across the individual satellite module or several such satellite modules collectively. Alternatively, each of the power generation tiles collocated on a satellite module may be controlled centrally.

[0098] A lightweight space structure refers to integral structures of movably interrelated elements used in the construction of the power generation tiles and/or satellite modules that may be configurable between at least packaged and deployed positions wherein the area and or dimensions of the power generation tiles and/or satellite modules may be reduced or enlarged in at least one direction. The lightweight space structures may incorporate or be used in conjunction with deployment mechanisms providing a deploying force for urging the movable elements between deployed and compacted configurations.

[0099] A large-scale space-based solar power station or simply solar power station refers to a collection of satellite modules being flown in an orbital array formation designed to function as one or more phased arrays. The one or more phased arrays may be operated to direct the collected solar radiation to one or more power receiving collectors.

[00100] Transmission characteristics of a power generation tile refer to any characteristics or parameters of the power transmitter of the power generation tile associated with transmitting the collected solar radiation to a power receiving collector via a far-field emission. The transmission characteristics may include, among others, the phase and operational timing of the power transmitter and the amount of power transmitted.

Structure of Large-Scale Space-Based Solar Power Station that Can Benefit from the Incorporation of the Described Mirrors

[00101] A large-scale space-based solar power station including a plurality of satellite modules positioned in an orbital array formation in a geosynchronous orbit about the Earth that can benefit from the incorporation of the described mirrors in accordance with certain embodiments of the invention is illustrated in Figure 7. The large-scale space-based solar power station 100 includes an array of independent satellite modules 102. The solar power station 100 is configured by placing a plurality of independent satellite modules 102 into a suitable orbital trajectory in an orbital array formation 104. The solar power station 100 may include a plurality of such satellite modules 1A through NM. In one instance, the satellite modules 1A through NM are arranged in a grid format as illustrated in Figure 7. In other instances, the satellite modules are arranged in a non-grid format. For example, the satellite modules may be arranged in a circular pattern, zigzagged pattern or scattered pattern. Likewise, the orbit may be either geosynchronous 106, which is typically at an altitude of 35,786 km above the Earth, or low Earth 108, which is typically at an altitude of from 800 to 2000 km above the Earth, depending on the application of the solar power station. As can readily be appreciated,

any orbit appropriate to the requirements of a specific application can be utilized by these described space-based solar power stations.

[00102] In some instances, the satellite modules in the solar power station are spatially separated from each other by a predetermined distance. By increasing the spatial separation, the maneuverability of the modules in relation to each other is simplified. As discussed further below, the separation and relative orientation of the satellite modules can impact the ability of the power generation tile on each of the satellite modules to operate as elements within a phased array. In one instance, each satellite module 1A through NM may include its own station keeping and/or maneuvering propulsion system, guidance control, and related circuitry. Specifically, as illustrated in Figure 8, each of the satellite modules 102 of the solar power station 100 may include positioning sensors to determine the relative position 110 of the particular satellite module 1A through NM in relation to the other satellite modules 1A to NM, and guidance control circuitry and propulsion system to maintain the satellite module in a desired position within the arbitrary formation 104 of satellite modules during operation of the solar power station. Positioning sensors can include the use of external positioning data from global positions system (GPS) satellites or international ground station (IGS) network, as well as onboard devices such as inertial measurement units (e.g., gyroscopes and accelerometers), and combinations thereof. In several instances, the positioning sensors can utilize beacons that transmit information from which relative position can be determined that are located on the satellite modules and/or additional support satellites. The guidance control and propulsion system may likewise include any suitable combination of circuitry and propulsion system capable of maintaining each of the satellite modules in formation in the solar power station array 104. In many instances the propulsion system may utilize, among others, one or more of chemical rockets, such as biopropellant, solid-fuel, resistojet rockets, etc., electromagnetic thrusters, ion thrusters, electrothermal thrusters, solar sails, etc. Likewise, each of the satellite modules may also include attitudinal or orientational controls, such as, for example, reaction wheels or control moment gyroscopes, among others.

[00103] In many instances, as illustrated in Figure 9, each satellite module 1A through NM of the solar power station 100 comprises a space structure comprised of one or more interconnected structural elements 111 having one or more power generation tiles 112 collocated thereon. Specifically, each of the satellite modules 1A through NM is associated with an array of power generation tiles 112 where each of the power generation tiles of the array each independently collect solar radiation and convert it to electric current. Power transmitters convert the electrical current to a wireless power transmission that can be received by a remote power receiving station. As discussed above, one or more power transmitters on each of a set of power generation tiles can be configured as an element in one or more phased arrays formed by collections of power generation tiles and satellite modules of the overall solar power station. In one instance, the power generation tiles in the satellite module are spatially separated from each other by a predetermined distance. In other instances, the construction of the satellite modules is such that the power generation tiles are separated by distances that can vary and the distributed coordination of the power generation tiles to form a phased array involves the control circuitry of individual power transmitters determining phase offsets based upon the relative positions of satellite modules and/or individual power generation tiles.

[00104] Power generation tiles 112 in many instances include a multicomponent structure including a photovoltaic cell 113, a power transmitter 114, and accompanying control electronics 115 electrically interconnected as required to suit the needs of the power transmission application. As illustrated in Figure 10a, in some instances photovoltaic cells 113, may comprise a plurality of individual photovoltaic elements 116 of a desired solar collection area that may be interconnected together to produce a desired electrical current output across the power generation tile. Some power transmitters 114 include one or more transmission antennas, which may be of any suitable design, including, among others, dipole, helical and patch. In the illustrated instance, a conventional patch antenna 114 incorporating a conductive feed 117 to conductively interconnect the RF power from the control electronics 115 to the antenna 114. As can readily be appreciated the specific antenna design utilized is largely

dependent upon the requirements of a specific application. Some power transmitters 114 are physically separated from one or both of the photovoltaic cell 113 and/or the control electronics 115 such as by fixed or deployable spacer structures 118 disposed therebetween. Some control electronics 115 may include one or more integrated circuits 119 that may control some aspect of the power conversion (e.g., to a power emission such as collimated light or an radio frequency (RF) emission such as microwave radiation), movement and/or orientation of the satellite module, inter- and intra-satellite module communications, and transmission characteristics of the power generation tile and/or satellite module. Further conductive interconnections 120 may connect the control electronics 115 to the source power of the photovoltaic cell 113. Each of the power generation tiles may also include thermal radiators to control the operating temperature of each of the power generation tiles.

[00105] In some instances, the PV 113 is a multi-layer cell, as illustrated in Figure 10b, incorporating at least an absorber material 113' having one or more junctions 113'' disposed between a back contact 121 on a back side of the absorber material and a top radiation shield 122 disposed on the surface of the absorber material in the direction of the incident solar radiation. The PV may include any electrical device that converts the energy of light directly into electricity by the photovoltaic effect including elements made from polysilicon and monocrystalline silicon, thin film solar cells that include amorphous silicon, CdTe and CIGS cells, multijunction cells, perovskite cells, organic/polymer cells, and various alternatives thereof. In some instances the photovoltaic material used within the PV cell is made from a thin film of GaInP/GaAs that is matched to the solar spectrum. Radiation shielding may include a solar radiation transparent material such as SiO_2 or glass, among others. The back contact may be made of any suitable conductive material such as a conductive material like aluminum, among others. The thickness of the back contact and top radiation shield may be of any thickness suitable to provide radiation shielding to the PV. Additional structures may be provided around the PV to increase the efficiency of the absorption and operation of the device including, for example, one or more concentrators that gather and focus incoming solar radiation on the PV, such as a Cassegrain, parabolic, nonparabolic, hyperbolic geometries or

combinations thereof. The PV may also incorporate a temperature management device, such as a radiative heat sink. In some instances the temperature management device is integrated with the control electronics and may be configured to control the operating temperature of the PV within a range of from ~150 to 300 K. Particularly effective configurations for power generation tiles are discussed in a subsequent section of this application.

[00106] In a number of instances, the power transmitters that are components of power generation tiles are implemented using a combination of control circuitry and one or more antennas. The control circuitry can provide the power generation tile with the computational capacity to determine the location of the power generation tile antenna(s) relative to other antennas within the satellite module and/or the solar power station. As can readily be appreciated, the relative phase of each element within a phased array is determined based upon the location of the element and a desired beam direction and/or focal point location. The control circuitry on each power generation tile can determine an appropriate phased offset to apply to a reference signal using a determined location of the power generation tile antenna(s) and beam-steering information. In certain instances, the control circuitry receives position information for the satellite module and utilizes the position information to determine the location of the power generation tile antenna(s) and determine a phase offset to apply to a reference signal. In other instances, a central processor within a satellite module can determine the locations of antennas on power generation tiles and/or phase offsets to apply and provides the location and/or phase offset information to individual power generation tiles.

[00107] In many instances, the positional information of each tile is received from partially redundant systems, such as, but not limited to, gyroscopes, accelerometers, electronic ranging radar, electronic positioning systems, phase and/or timing information from beacons, as well as employing a priori knowledge from system steering and flight control commands. In several instances, electronic systems are located on the ground, and/or in space on satellites deployed for this purpose (and, possibly, other purposes, e.g. in the case of using GPS satellites).

[00108] In a number of instances, position information may be relayed in a hierarchical fashion between modules, panels and/or tiles within the space-based solar power station, such that a central processing unit relays positional information such as location and orientation of the entire space-based solar power station with respect to a ground station and/or other suitable known locations to modules within the system. The relayed information can be expressed as an absolute and/or differential location(s), and/or orientation(s) as appropriate to the requirements of specific applications. In a similar fashion, the location and/or orientation of each module with respect to the center of the space-based solar power station or other suitable reference point can be determined at each module using processes similar to those outlined above. Furthermore, going down a hierarchical level, the position and orientation information of individual panels and tiles can be determined in a similar fashion. The entirety or any useful part of this information can be used at the tile-level, the panel-level, the module-level, the system-level and/or any combination thereof to control the phase and/or amplitude of each tile radiator to form a beam or focal spot on the ground. The aggregate computational power of the computational resources of each tile, panel and/or module can be utilized since each tile (and/or panel or module) can utilize its local computational power available from a DSP, microcontroller or other suitable computational resource to control its operation such that the system in aggregate generates the desired or close-to desired beam and/or focused transmission.

[00109] In various instances, as illustrated conceptually in Figure 10c, power generation tile control circuitry can be implemented using one or more integrated circuits. An integrated circuit 123 can include an input/output interface 124 via which a digital signal processing block 125 can send and receive information to communicate with other elements of a satellite module, which typically includes a processor and/or memory configured by a control application. In certain instances, the digital signal processing block 125 receives location information (see discussion above) that can be utilized to determine the location of one or more antennas. In many instances, the location information can include a fixed location and/or one or more relative locations with respect to a reference point. The digital signal processing block can utilize the

received location information and/or additional information obtained from any of a variety of sensors including (but not limited to) temperature sensors, accelerometers, and/or gyroscopes to determine the position of one or more antennas. Based upon the determined positions of the one or more antennas, the digital signal processing block 125 can determine a phase offset to apply to a reference signal 126 used to generate the RF signal fed to a specific antenna. In the illustrated instance, the integrated circuit 500 receives a reference signal 126, which is provided to an RF synthesizer 127 to generate an RF signal having a desired frequency. The RF signal generated by the RF synthesizer 127 is provided to one or more phase offset devices 128, which are configured to controllably phase shift the RF signal received from the RF synthesizer. The digital signal processing block 125 can generate control signals that are provided to the phase offset device(s) 128 to introduce the appropriate phase shifts based upon the determined location(s) of the one or more antennas. In many instances, the amplitude of the generated signal can be modulated and/or varied alone or in conjunction with the phase appropriately upon the determined locations to form the power beam and/or focused transmission. The amplitude can be modulated in variety of ways such as at the input of a power amplifier chain via a mixer or within an amplifier via its supply voltage, an internal gate or cascade biasing voltage. As can readily be appreciated, any of a variety of techniques appropriate to the requirements of a specific application can be utilized to amplitude modulate an RF signal. The phase shifted RF signals can then be provided to a series of amplifiers that includes a power amplifier 129. While the entire circuit is powered by the electric current generated by the PV component(s) of the power generation tile, the power amplifier is primarily responsible for converting the DC electric current into RF power that is transmitted via the RF signal. Accordingly, the power amplifier increases the amplitude of the received phase shifted RF signal and the amplified and phase shifted RF signal is provided to an output RF feed 130 connected to an antenna. In many instances, the RF signal generated by the RF synthesizer is provided to an amplifier 131 and distributed to the control circuitry of other tiles. The distribution of reference signals between tiles in a module in accordance with various instances is discussed further below.

[00110] Although specific integrated circuit implementations are described above with reference to Figure 10c, power generation tile control circuitry can be implemented using any of a variety of integrated circuits and computing platforms in a variety of instances. Furthermore, satellite modules can be implemented without providing computational capabilities on each power generation tile and/or without utilizing the computational capabilities of a power generation tile to determine locations and/or phase shifts for the purposes of generating an RF signal to feed a power generation tile antenna.

[00111] In many instances, as illustrated conceptually in Figure 11, a plurality of power generation tiles 112 on each satellite module may each form a panel 160 of a modular phased array 162 incorporating at least self-contained, collocated photovoltaics, power transmitters and control electronics within each power generation tile. The control electronics may allow for wire or wireless communications between the individual power generation tiles for the exchange of timing and control information. The array of control electronics may also allow for the exchange of control and timing formation with other satellite modules. Collocation of at least the power collection, far-field conversion, and transmission elements on each modular power generation tile allows for the each power generation tile to operate as an independent element of the phased array without inter- and intra- module power wiring.

[00112] In one instance, the power generation tiles and/or satellite modules may include other related circuitry. The other circuitry may include, among others, circuitry to control transmission characteristics of the power generation tiles, thermal management, inter or intra-module communications, and sensors to sense physical parameters, such as orientation, position, etc. The control circuitry may control transmission parameters such as phase and timing information such that the arrays of power generation tiles across each module and across the solar power station may be operated as independent array elements of one or more phased arrays. The sensors may include gyroscopes, GPS or IGS devices to estimate position and orientation, and thermocouples to estimate the temperature on the power generation tiles.

[00113] In one instance, the circuits for controlling transmission characteristic parameters may be collocated on the several power generation tiles or satellite modules and may control each transmitter of each power generation tile independently or in a synchronized manner such that the tiles operate as one or more element of one or more phased arrays. Reference signals (e.g., phase and timing) that can be used to synchronize the operation of the power generation tiles as a phased array may be generated locally on each power generation tile or satellite module and propagated via wired or wireless intra and inter-module communications links, or may be generated centrally from a single source on a single satellite module and propagated via wired or wireless intra and/or inter-module communications links across each of the satellite modules and power generation tiles. In addition, one or multiple timing reference signals may be generated from outside the space-based solar power station system such as one or more satellites flying in close proximity or even in different orbits; as well as from one or more ground stations.

[00114] Each power generation tile or satellite module may be operated independently or collectively as an element in a phased array. Entire or most operations associated with each individual power generation tile may be collocated on each of the power generation tiles or collectivized within the satellite module on which the power generation tiles are collocated, or across multiple satellite modules. In one instance, a central reference signal is generated and deviation (e.g., phase) from such reference signal is determined for each power generation tile array element of the phased array. By propagating a central reference signal from the reference signal, higher levels of control abstraction can be achieved to facilitate simpler programming for many operations of the phased array.

[00115] In some instances, each power generation tile of each satellite module may be the same or different. The number of distinct combinations of photovoltaic cells, transmission modules and control electronics may be as large as the number of power generation tiles in the satellite modules. Further, even where each of the power generation tiles on a satellite module are the same, each of the satellite modules 1A through NM or a group of satellite modules may have different solar radiation collection or transmission characteristics or may have arrays of power generation tiles of different sizes, shapes and configurations.

[00116] In certain instances, the solar power station is designed as a modular phased array where the plurality of satellite modules and power generating tiles located thereon form the array elements of the phased array. For this purpose, each of the satellite modules may be designed to be physically compatible with conventional launch vehicles although the achieved power generation of the phased array of the solar power station may exceed conventional space-based solar power satellites in many respects. Taking advantage of the increased performance, the solar power station phased array in this case may include smaller payload size and overall array size to obtain equal or better power generation compared to conventional space-based solar power satellites. Alternatively, the size of the overall solar power station may be reduced compared to solar platforms in conventional solar power satellites while achieving comparable results.

[00117] In order to match the power generation of a conventional solar power satellite without increasing platform size or weight, the power collection, transmission and control logic for the individual power generation tiles is preferably collocated within each of the power generation tiles or within the satellite module on which the power generation tiles are collocated thus eliminating the need for intra- or inter-module communications, wiring or structural interconnection. In one instance, much of the power transmission control logic is a single collection of functions common to all or most of the power generating tiles. In this instance, the conventional external intra- and inter-power generation tile infrastructure for the solar power station may be entirely eliminated thus reducing the power generated per weight unit (W/kg).

[00118] In one instance, the phased array of the solar power station including the satellite modules and power generation tiles replaces a conventional monolithic solar power satellite. The solar power stations includes *N x N* satellite modules, each module including power generation tiles of $\frac{M}{N^2}$. Table 3 lists example configurations of solar power stations.

Efficiency Standards		**SPS Configuration Parameters**				
Solar Cell Efficiency	35 %	SPS Configuration	W/kg	Max Size	Exemplary Phased Array System Performance*	
DC-Microwave Conversion	78 %	USEF	41	100 x 95 m	Power Received	12 GW
Collection Efficiency	86 %	JAXA	98	3.5 km	Power Received/Module	1.72 MW
Transmission Efficiency	77 %	ESA	132	15 km	Power Received Rectenna	1.34 GW
Atmospheric Absorption	< 2 %	Alpha	33	6 km	Rectenna size:	6.65 km
Overall	14 %	Modular Phased Array	2270	60 x 60 m	Total mass (avg: 100 g/m^2)	900000 kg
• Assuming a Solar Power Station having a 50 x 50 array of 60 x 60 m satellite modules in a geosynchronous orbit with a 1GHz power transmission having a a/λ = 0.5, and a solar irradiance of 1400 W/m^2.						

[00119] The Conventional SPS performance in Table 3 are taken from published literature. The Exemplary Phased Array System Performance in Table 3 are estimates and may differ based on the actual design parameters implemented.

[00120] The number of power generation tile array elements in each satellite module, and the number of satellite modules in the solar power station may be determined based on, among other factors, power requirements, payload restrictions, etc. A first factor for the size of an overall solar power station is the power to be generated at the power receiving rectenna. As illustrated in Figure 12, in certain instances the power incident on the ground using a far-field RF emission can have a maximum power lobe (u_{max}) that is dependent on factors including (but not limited to) the size of the array, the wavelength of the RF transmission, and the phase offset error tolerated within the phased array. For example, in instances of a 50 x 50 array of satellite modules in a solar power station formed by 60 x 60 m satellite modules a maximum power lobe of 926 W/m^2 is estimated to be generate on the ground with a sidelobe level of 44 W/m^2. The incident area of the maximum power lobe with a 1 GHz emission is estimated to

have a diameter of 6.6 km, while the incident area is estimated to have a diameter of 2.8 km for a 2.4 GHz emission. From a power transmission point of view, the preferred number of elements in the phased array formed by a solar power station and the wavelength of the transmission will depend on the size of the receiving rectenna and/or array of receiving rectennas. In many instances it is desirable to have the maximum power lobe on the ground coextensive with the rectenna area.

[00121] In certain instances this limitation many also be overcome by dividing the power transmission output 176 of the solar power station 174 between different rectenna power receivers 178, as illustrated conceptually in Figure 13. In many instances, different collections of elements (e.g., satellite modules and/or power generation tiles) forming part of the solar power station 174 may be configured into different phased arrays that may be simultaneously directed at different rectenna power receivers 178 on the ground thus potentially reducing the individual incident areas radiated by the solar power station. In some instances additional control circuitry is provided either within the satellite module or within each of the power generation tiles to allow for dynamic electronic steering of the transmission beam, either from the collective power generation tiles of a satellite module or from each power generation tile independently. In some instances the power steering circuitry may allow for the control of the relative timing (phase) of the various power transmitters on the power generation tile array elements, as illustrated conceptually in Figures 14a and 14b, such that each transmission beam may be redirected electronically at micro- and/or nano-second time scales. The power transmission from such dynamically steerable phased array on a solar power station allows for the entire phased array or portions thereof to be dynamically redirected in different directions dependent on demand at one or more rectenna power receivers. Many instances characterized by such dynamically directable phased arrays on power solar stations may be used to redirect the power transmission in different directions at micro and nano-second time scales by electronic steering. Certain instances also allow for power transmissions to be dynamically distributed to various ground stations either simultaneously or sequentially based on instantaneous local demand. Power levels at each of such rectenna receivers may also

be dynamically adjusted. Rapid time domain switching of power amongst rectenna receivers can also be used to control duty cycle and alleviate large scale AC synchronization issues with respect to an overall power grid.

[00122] A second factor that may constrain the number of array elements in any satellite module is the issue of payload size and weight. Current payload delivery technologies for geosynchronous orbits range from 2,000 to 20,000 kg. Accordingly, the limit to the size of any single satellite module is the actual lift capacity of available payload delivery vehicles. Based on an assumption of 100 g/m^2 for the phased array satellite modules, a 60 x 60m satellite module would have a weight of 360 kg, well within the limits of current delivery technologies. Larger modules could be produced provided they are within the lift capacity of available lift vehicles.

[00123] In some instances, satellite modules are compactable such that the size of the satellite module in one or more dimensions may be reduced during delivery to overcome payload space constraints and then expanded into its final operating configuration. As illustrated in Figures 15a and 15b, in many instances the solar power station 180 includes an array of satellite modules 182, each satellite module comprising a plurality of structural elements 184 that are movably interconnected such that the plurality of structural elements may be moved between at least two configurations: a deployed configuration (FIG. 15a) and a compacted configuration (15b), such that the ratio of the packaged volume to the material volume is larger in the deployed configuration when compared to the compacted or packaged configuration. In some instances, the structural elements 184 may be hinged, tessellated, folded or otherwise interconnected 186 such that the structural elements can move in relation to each other between the compacted and deployed configurations. Each satellite module of a solar power station may be configured to compact to the same or different sizes. In addition, different compacting methods may be used to compact one or more satellite modules of a solar space station, including, among others, one and two-dimensional compaction structures. In some instances, one or a combination of z-folding, wrapping, rolling, fan-folding, double z-folding, Miura-ori, slip folding and symmetric wrapping may be used, among others.

[00124] In many instances the power generation tiles may have further compactible and expandable features and structures disposed thereon. In some instances of power generation tiles the photovoltaic cell and power transmitter may be movably interrelated through a compactable structure, such that when in a compacted or packaged configuration the elements of the power generating cell are compressed together to occupy a total volume lower than when in a deployed configuration. In some deployed configurations the photovoltaic cell and power transmitter are separated by a gap (e.g., to create a vertical offset therebetween). Certain instances having a compactable structure include motorized interconnections and resilient members such as spring or tension arms that are bent or under compression, among others. Such compactable structures may also incorporate packaging techniques such as one or a combination of z-folding, wrapping, rolling, fan-folding, double z-folding, Miura-ori, slip folding and symmetric wrapping may be used, among others.

[00125] The power generation tiles and/or satellite modules may include other structures to enhance the collection of solar radiation or transmission of power from the power generation tiles and/or satellite modules. Structures that may be incorporated into power generation tiles and/or satellite modules may include, among others, thermal radiators for controlling the thermal profile of the power generation tiles, light-collecting structures (e.g., radiators, reflectors and collectors) to enhance the efficiency of solar radiation collection to the photovoltaic cell, and radiation shielding to protect the photovoltaic cells, power transmitters and/or control electronics from space radiation. Such structures may also be independently compactible, between packaged and deployed configurations, as described above in relation to other elements of the power generation tiles.

[00126] A design for a satellite module or power generation tile may be applied to different satellite modules or power generation tiles. Other variables in the solar power station such as spatial distances, photovoltaics, power transmitter, control electronics and combinations with may be modified to produce a phased array with differing power collection and transmission characteristics. In this way, a diverse mix of solar power stations may be produced while maintaining the benefits of the modular solar power station described.

Compactable Space Structures that can Benefit from the Incorporation of the Described Mirrors

[00127] In many instances, the satellite modules of the solar power station employ compactible structures which can benefit from the incorporation of mirrors in accordance with certain embodiments of the invention. Compactable structures allow for the satellite modules and/or power generation tiles to be packaged in a compacted form such that the volume occupied by the satellite module and/or power generation tiles can be reduced along at least dimension to allow for the satellite modules to fit within an assigned payload envelope within a delivery vehicle. Several exemplary instances of possible packaging schemes are provided, however, it should be understood that the packaging procedure and compactible structures may involve, among other procedures, using one and two-dimensional compaction techniques, including, one or a combination of z-folding, wrapping, rolling, fan-folding, double z-folding, Miura-ori, star folding, slip folding and wrapping.

[00128] In many instances a two-dimensional compacting technique may be utilized to package and deploy the satellite modules and/or power generation tiles. Figure 16 provides a perspective view of a satellite module 290 with a plurality of power generation tiles 292. The plurality of power generation tiles 292 in this instance are hinged together and tessellated into a Miura-ori folding pattern such that the satellite module is compacted biaxially along an X and Y axis. Although the hinges interconnecting the panels may be made of any suitable design, in one instance the

hinged elements are interconnected by carbon fiber rods or other suitable support structure. Images of a membrane being folded are provided in Figure 17.

[00129] In many instances a slip-wrapping compacting technique may be utilized to package and deploy the satellite modules and/or power generation tiles. Figures 18a to 18d provide cross-sectional views of the construction of instances of the slip-wrapping technique. As shown, in these instances two elongated elements 300 and 302 interconnected at a first end 304 and open at a second end 306 (FIG. 18a) are wrapped about a hub (FIG. 18b). Such wrapping causes one of the elongated elements 300 to slip along its longitudinal length with respect to the second elongated element 302 such that a gap 308 forms between the unconnected ends of the elements. A second set of such elongated elements 310 and 312 interconnected at one end 314 are then obtained by a 180º rotation of the first set of elongated elements and the non-interconnected ends are then joined together 316 to form a single elongated element of an undulating configuration 318 interconnected at both ends 304 and 314 (FIG. 18c). The undulating strip thus formed may then be wrapped about a hub of a specified radius 320 that is no smaller than the minimum bend radius of the material of the elongated element thus reducing the dimensions of the satellite module biaxially in both an X and a Y axis (Fig. 18d).

[00130] Some instances of a slip-wrap packing technique as applied to a compactible satellite module 350 are shown in a perspective view in Figure 19. In one instance the satellite module is formed of a plurality of elongated structures 352 that are interconnected at two ends 354 and 356, but that are allowed to shear along their edges. During packaging the elongated structures are first folded with z-fold to form an elongated plurality of structures that are compacted along a first axis 358 orthogonal to the longitudinal axis 360 of the elongated structures. The compacted elongated structures are then wrapped about a hub with a radius 362 (which is selected to be no smaller than the minimum bend radius of the elongated structures of the satellite module) to further compact the strips along a second axis, thereby forming a fully compacted satellite module. Although a satellite module with an overall rectangular configuration are shown in Figures 18 and 19, it should be understood that the

technique may be implemented with any configuration, number or shape of individual strip elements so long as they are joined at the edges and the edges are permitted to shear as described above. Images of a compactible structure using a diagonal z-fold are provided in Figure 20. The deployed square of 0.5 m may be packaged into a cylindrical structure with a diameter of 10 cm and a height of 7 cm.

[00131] Using such techniques it is possible to significantly reduce the packaging volume of the satellite modules. In one exemplary instance where the compactible structures of a satellite module have a tile/panel thickness of 1 cm and a minimum bend radius of 10 cm, a satellite module with a deployed area of 60 m x 60 m and being comprised of 30 such compactible structures would be compactible using the slip-wrap packaging technique into cylindrical package with a diameter of 5 m and a height of 2 m.

[00132] In many instances, the number of compactible elements in each of the satellite modules in a solar space station may be the same or different and may contain one or more power generation tiles collocated thereon. One or more compacting techniques may be used in packaging the compactible elements of each of the satellite modules and the techniques use may also the same or different. In many instances the compacting techniques utilized to package the satellite modules prior to deployment reduce the packaging volume of the satellite module in at least one dimension such that the satellite module fits within the allowed payload volume of the selected delivery vehicle.

[00133] In many instances, the power generation tiles may have further compactible and expandable features and structures disposed thereon. In some instances, power generation tiles, the photovoltaic cell, and power transmitter may be movably interrelated through a compactable structure, such that when in a compacted or packaged configuration the elements of the power generation tile are compressed together to occupy a total volume lower than when in a deployed configuration. In some deployed configurations the photovoltaic cell and power transmitter are separated by a gap (e.g., to create a vertical offset therebetween). Some instances of compactable structure include motorized interconnections and resilient members such as spring or

tension arms that are bent or under compression, among others. Such compactable structures may also incorporate packaging techniques such as one or a combination of z-folding, wrapping, rolling, fan-folding, double z-folding, Miura-ori, slip folding and symmetric wrapping may be used, among others.

[00134] In many instances, deployment mechanisms are provided to deploy the compacted satellite modules (e.g., move the compactible elements of the satellite module from a compacted to a deployed configuration). In many instances, an active or passive mechanism is interconnected with one or more portions of the compactible structures of the satellite module such that when activated the compacted structures of the satellite modules may be expanded into a deployed operational configuration.

[00135] In some instances, a mechanically expandable member may be incorporated into the satellite module. An illustration of such a satellite module is provided in Figure 21 where a satellite module 400 having a plurality of compactible structures 402 are disposed about a central hub 404. The compactible structures 402 are interconnected on at least one edge with a mechanically expandable member 406 such that as the mechanical member is urged outward the compactible structures are also expanded outward from the central hub. The expandable member may be motorized or may use stored energy, such as, compressed or bent expandable members, among others.

[00136] In many instances the compactible structures of the satellite module may be configured such that motion of the satellite module provides the expansive deployable force. An illustration of one such instance is provided in Figure 22 where weighted elements 420 are attached between a central hub 422 and at least a portion of each of the compactible structures 424 of the satellite module 426 such that when the central hub of the satellite module is spun the centrifugal force of the spinning hub causes the weighted elements to move outward thereby expanding the compactible structures. In such instances, the satellite module may be made to spin continuously to provide a stabilization force to the compactible structures.

[00137] Regardless of the mechanism chosen, in many instances, the satellite module may be divided into any number and configuration of separate compactible structures with any number of hubs and deployment mechanisms (e.g., expandable members, weighted elements, etc.). In many instances, the compactible structures are attached along at least two edges to more than one deployment mechanism such that more even expansion of the compactible structures may be obtained. In many instances, for example, multiple weights or expandable members may be attached to each of the compactible structures along multiple points or edges of the compactible structures. Some expandable members or weighted elements may be incorporated into the structure of the compactible structures. Many instances of deployment mechanisms may include deployment controls to controllably operate the compactible structures of the satellite modules so that the satellite modules are expanded into a deployed configuration when desired. Some instances of such deployment controls may be automated, such that the positioning or motion of the satellite hub automatically engages the deployment mechanism, such as, for example, by spinning the satellite module at a specified rate. Other instances may incorporate control circuits such that an external signal or command is required to activate the deployment mechanism. Such deployment controls may operate across an entire satellite module, may be disposed individually in each power generation tile, or a combination thereof.

Efficient Power Generation Tile Configurations

[00138] In many instances, particularly efficient power generation tiles are implemented within Space-based Solar Power Stations that can benefit from incorporating the above-described mirrors. The implementation of such power generation tiles within the described SBSP systems can make them more practicable insofar as they can offer greater power generation per unit mass. As can be appreciated, power generation tiles having a reduced mass can be advantageous for at least two reasons: (1) they can allow for reduced launch costs – i.e. a reduced payload can be cheaper to send into outer space; and (2) they can enable easier maneuverability of corresponding satellite modules. Against this backdrop, in many

instances, thin film, pliable, photovoltaic materials that create an electrical current from solar radiation are implemented; the thin film photovoltaic materials can be used in conjunction with lightweight substrates for structural support. As can be appreciated, a photovoltaic material can be understood to be a contiguous material having a structure whereby the receipt of incident light (photons) excites electrons to a conduction band to a useful extent, and thereby allows for the creation of a useful electrical current. In a number of instances, concentrators are implemented that redirect solar radiation toward an associated photovoltaic material, such that the photovoltaic material can experience greater solar flux relative to the case where no concentrators are used. As can be appreciated, the amount of electrical current that a corresponding PV cell is able to produce is directly related to the incident solar radiation (accounting for its concentration/flux). In this way, for a given target power generation value, the utilization of concentrators can allow the amount of photovoltaic materials used, along with respective attendant radiative shielding (which can be relatively massive), to be reduced. In several instances, configurations are implemented that facilitate the radiative cooling of the photovoltaic materials, which can allow them to generate power more efficiently. For example, in many embodiments, structures that are sized approximately on the order of wavelengths of thermally radiated light and are otherwise configured to effectively increase the emissivity of the of power generation tiles, and thereby contribute to the radiative cooling of the photovoltaic materials, are implemented.

[00139] In many instances, a thin film photovoltaic material is implemented, such as those used in a typical III-V solar cell, to produce electrical current from incident solar radiation. Thus, for instance, in many instances, a Gallium Arsenide thin film photovoltaic material is implemented, such as those developed by ALTADEVICES. Figures. 23A and 23B illustrate performance data pertaining an ALTADEVICES photovoltaic material that can be incorporated in accordance with certain instances. In particular, Figure 23A depicts the current vs. voltage characteristics of an X25 IV System, while Figure 23B depicts a normalized QE performance as a function of electromagnetic wavelength. ALTADEVICES thin film photovoltaic materials have

demonstrated efficiencies as high as: 28.8% for a single junction configuration; 31% for a dual junction configuration; and 36% for a triple junction configuration. As can be appreciated, multi-junction PV cells can produce electric current for a broader range of electromagnetic wavelengths, and can thereby demonstrate greater conversion efficiencies. Note that this data was obtained under conditions of 1 Sun and 1.5 atmospheric G. Of course, it should be realized that, while the implementation of ALTADEVICES photovoltaic materials has been discussed, any suitable photovoltaic materials can be incorporated in a variety of instances. In other words, the described instances are not constrained to the implementation of photovoltaic materials produced by ALTADEVICES. For example, in many instances, power generation tiles include photovoltaic materials fabricated by SPECTROLABS. In a number of instances, power generation tiles include photovoltaic materials fabricated by SOLAERO TECHNOLOGIES. Any thin film photovoltaic materials that are characterized by desirable pliability and durability can be implemented.

[00140] Notably, in many instances when photovoltaic materials are implemented in outer space, they are typically accompanied by radiation shields that protect them from deleterious radiation. The radiation shields are typically in the form of cover glass, which can be relatively massive. To provide context, Figure 24 illustrates a typical configuration for a PV Cell that is to be implemented in outer space. In particular, Figure 24 depicts that a typical configuration for a PV cell includes a photovoltaic material disposed on a back contact and covered by a radiation shield. Note that it is typical for the entire surface area of a photovoltaic material to be protected by radiation shielding. Thus, implementing photovoltaic materials having relatively more surface area generally involves implementing correspondingly more radiation shielding. As radiation shielding (commonly in the form of cover glass) can be relatively massive, including more radiation shielding can non-negligibly increase the mass of the power generation tile, which can be undesirable. Accordingly, many instances implement configurations that reduce the amount of radiation shielding, while preserving power generation efficiency. For example, in many instances, concentrators are incorporated that can reduce the amount of photovoltaic material required for a target power generation value. In effect,

the amount of photovoltaic cell surface area is reduced by relatively less massive concentrators.

[00141] Moreover, in many instances power generation tile configurations are implemented that facilitate the cooling of the photovoltaic materials, e.g. by using microstructures. The use of microstructures to facilitate the cooling of photovoltaic materials is discussed in U.S. Pat. App. No. 62/269,901, the disclosure of which is hereby incorporated by reference in its entirety. As can be appreciated, photovoltaic materials can heat up extensively during operation, and heat can adversely impact a photovoltaic material's ability to produce electrical current. To provide context, an energy balance for a sample solar cell in operation is depicted in Figure 25. In particular, an ALTADEVICES Dual Junction Cell having a conversion efficiency of 31% is illustrated. The Dual Junction Cell experiences a solar flux of 1354 W/m^2, of which 522 W/m^2 is reflected. Correspondingly, 832 W/m^2 is absorbed by the Dual Junction Cell, of which 419 W/m^2 is converted into electrical energy, and 413 W/m^2 of which is rejected as heat. In general, the rejection of heat reduces the operating temperature of the photovoltaic material so as to benefit its power generation efficiency.

[00142] In many instances, configurations are implemented that provide improved power generation per unit mass. For instance, in many instances concentrators are implemented that concentrate solar radiation onto a corresponding photovoltaic material such that the photovoltaic material experiences greater solar flux relative to if the photovoltaic material were subjected to unaltered solar radiation. As can be appreciated a photovoltaic material's ability to generate electrical current is related to the amount of incident solar radiation / flux. Note that concentrators can be made to be less massive than the combined mass of conventional PV Cells including radiation shielding. Accordingly, the incorporation of concentrators can reduce the amount of photovoltaic material for a given desired power generation value, and can correspondingly reduce the amount of radiation shielding implemented.

[00143] As already alluded to above, the concentrators can take any suitable form in accordance with many instances. For example, in many instances, concentrators are implemented in the form of mirrors, as already discussed above.

[00144] Importantly, concentrators can be implemented in any of a variety of geometric configurations. For example, in many instances, Cassegrain configurations are implemented; Cassegrain configurations are typically characterized by primary and secondary reflectors that redirect solar radiation onto a photovoltaic material (typically disposed on the primary reflector). Typically, a primary reflector redirects incident solar radiation onto a secondary reflector, which subsequently redirects incident solar radiation onto a photovoltaic material. Note that a reflector can be understood to be that portion of a concentrator which directly reflects incident solar radiation. For example, Figures 26A-26C illustrate a Cassegrain configuration that can be implemented. In particular, Figure 26A depicts an isometric view of the iterative Cassegrain configuration. Figure 26B illustrates a cross-sectional view of a single Cassegrain cell within a Cassegrain configuration. In particular, it is illustrated that the Cassegrain cell 2002 includes a primary reflector 2004, a complementary secondary reflector 2006, a photovoltaic material 2008, and a radiative heat sink 2010 that can facilitate the rejection of thermal energy by the photovoltaic material 2008. As can be appreciated from the above discussion, the reflectors can be implemented using any suitable material in a number of instances. Similarly, they can be disposed on any suitable substrate, including but not limited to a KAPTON polyimide film.

[00145] Figure 26C illustrates the generalized understanding of the operating principles of Cassegrain configurations. In particular, it is illustrated that for a Cassegrain structure 2012, it is generally understood that light rays 2015 are redirected by a primary reflector 2014 onto a secondary reflector 2016, and subsequently onto a photovoltaic material 2018. It should be clear that the described instances are not constrained to the precise manifestation of these operating principles. Rather, the understood generalized operating principles are discussed here to facilitate the understanding of the structure.

[00146] Note that the reflectors implemented in Cassegrain structures can incorporate any of a variety of complementary shapes to redirect – and focus – solar radiation onto a photovoltaic material. For example, in many instances, a primary reflector conforming to a parabolic shape is implemented, while a corresponding secondary reflector that conforms to a hyperbolic shape is implemented. Moreover, the particular characteristics of the parabolic and hyperbolic shapes can be adjusted based on the requirements of a particular application. For instance, the parabolic and hyperbolic shapes can be made to be wider or narrower based on desired design criteria. To be clear though, any suitable pairing of reflector shapes that redirect solar radiation onto a photovoltaic material can be implemented, and not just those conforming to parabolic/hyperbolic shapes.

[00147] Cassegrain structures, such as those illustrated in Figures 26A-26C, can be advantageous insofar as they can demonstrate good thermal properties. For example, as the photovoltaic materials are typically in direct contact with the primary reflector, the primary reflector can function has a heat sink for the photovoltaic material, and thereby facilitate radiative cooling. As the primary reflector can facilitate conductive cooling, it can be said to be in thermal communication with the photovoltaic material. Additionally, dedicated heat sinks can also be coupled to the photovoltaic material, as illustrated in Figure 26B. As can be appreciated, coupled heat sink structures can further assist the photovoltaic material in tending towards cooler, more preferable (e.g. efficient), operating temperatures.

[00148] While Cassegrain structures can exhibit advantageous thermal properties, they can be sensitive to solar radiation angle of incidence. For example, the secondary reflector can cast a shadow and thereby hinder solar flux received by the primary reflector, and eventually the photovoltaic material. Additionally, because of the somewhat sophisticated geometry, some angles at which solar radiation reaches the corresponding power generation tile may not be received. Moreover, because Cassegrain structures employ two reflectors, they are subject to more reflection loss relative to configurations that employ only a single reflector.

[00149] While Cassegrain structures have been discussed, it should be clear that any of a variety of concentrator configurations can be implemented. For example, in many instances, 'Parabolic Trough' configurations are implemented. Parabolic Trough configurations are similar to the Cassegrain structures discussed above, except that they do not include a secondary reflector; rather the primary reflector is used to redirect solar radiation onto an opposingly disposed photovoltaic material. For example, Figure 27 illustrates the generalized understanding of the operation of a Parabolic Trough configuration. In particular, it is illustrated that the Parabolic Trough configuration 2102 includes a parabolic reflector 2104, and an opposingly disposed photovoltaic material 2108. Light rays 2115 are depicted that are redirected by the parabolic reflector 2104 onto the photovoltaic material 2108. Again, it should be clear that the precise manifestation of these operating principles are not requisite. Rather, the understood generalized operating principles are discussed here to facilitate the understanding of the discussed structure. Additionally, it should be noted that while Figure 27 depicts the operation of a single Parabolic Trough unit, a power generation tile can of course includes a plurality of such Parabolic Trough units.

[00150] While the reflector can conform to any shape that redirects solar radiation to a photovoltaic material, it can be advantageous if it conforms to a parabolic shape so as to efficiently focus solar radiation onto the opposingly disposed photovoltaic material. Additionally, as can be appreciated from the discussion above, the configurations can be implemented using any of a variety of materials. For example, in many instances, the concentrator is implemented using a reflective surface, in conjunction with a lightweight substrate. Additionally, the photovoltaic material can be any suitable material, such as – but not limited to – thin film photovoltaics produced by ALTADEVICES.

[00151] Parabolic Trough configurations can be advantageous relative to Cassegrain structures in that, since they only employ a single reflector (as opposed to two reflectors), they are subject to less reflective loss relative to Cassegrain structures that implement two reflectors. However, as the photovoltaic material is not typically directly coupled to a large surface area such as the primary reflector (as in the case of a Cassegrain structure), Parabolic Trough configurations may not be as efficient at radiative heat transfer.

[00152] In many instances, a 'Venetian Blinds' configuration is implemented, whereby concentrators redirect solar radiation towards photovoltaic materials that are disposed on the backside of adjacently disposed concentrators. Figures 28A-28B illustrate a Venetian Blinds configuration that can be implemented in accordance with certain instances. More specifically, Figure 28A illustrates an isometric view of a Venetian Blinds configuration. In particular, it is depicted that the configuration 2200 includes a plurality of concentrators 2204, each having a photovoltaic material 2208 disposed on its backside. The photovoltaic materials are disposed such that the concentrators 2204 redirect solar radiation onto a photovoltaic material that is disposed the on backside of an adjacent concentrator. Figure 28B illustrates a generalized understanding of the operation of the Venetian Blinds configuration. In particular, it is illustrated that light rays 2215 are redirected by a respective reflector 2204 onto a photovoltaic material 2208 that is disposed on the backside of an adjacent reflector. As can be gathered from the above discussion, the reflectors 2104 can be curved so as to focus the solar radiation on to the targeted photovoltaic material 2208. It should be clear that the described configurations are not constrained to the precise manifestation of these operating principles. Rather, the understood generalized operating principles are discussed here to facilitate the understanding of the discussed structure.

[00153] Venetian Blinds configurations can be constructed using any of a variety of materials and techniques. For example, in several instances, Venetian Blinds configurations are implemented using polyimide films in conjunction with carbon springs, and reflectors. Figure 29A illustrates a cross section of a Venetian Blinds configuration that depicts materials that can be used in its construction. In particular, it is

illustrated that the Venetian Blinds configuration 2300 includes reflectors 2304 that are characterized by a reflective surface 2305 disposed on a KAPTON polyimide layer 2307, that is itself utilized in conjunction with a carbon springs 2309. As can be appreciated, the springs can help the power generation tile deploy, and also aid in structural integrity. The plurality of reflectors 2304 can be disposed on a KAPTON Polyimide substrate 2312. This recited combination of materials has been shown to be particularly effective for the intended operation, as the carbon springs and polyimide films have demonstrated sufficient pliability and durability for operation in space. Although, it should again be clear that while certain materials are referenced, any suitable materials can be incorporated. For instance, any of a variety of spring materials can be incorporated, including any of a variety of conductive spring materials, and non-conductive spring materials.

[00154] To provide context, Figure 29B illustrates a Venetian Blinds configuration in conjunction with a power transmitter. In particular, it is depicted that a Venetian Blinds configuration 2350 is disposed above a power transmitter 2360, and adjoined to the power transmitter via four "s-shaped" struts 2352. Of course it should be clear that the power transmitter and struts can be implemented in any of a variety of ways and can conform to any of a variety of suitable. The depiction is meant to be illustrative and not exhaustive of configurations that can be implemented.

[00155] Venetian Blinds configurations can be advantageous insofar as each of the concentrators can act as a heat sink for a coupled photovoltaic material, thereby facilitating conductive and radiative cooling, and consequently a more efficient operation. Additionally, in contrast to the Cassegrain configuration, only a single reflector is used in redirecting solar radiation onto a photovoltaic material. As alluded to above, using a single reflector can reduce the potential energy loss relative to configurations that incorporate a plurality of reflectors. In many instances, optical efficiencies of greater than 90% can be realized using Venetian Blind configurations. Moreover, such configurations can result in concentrations of between approximately 10x to approximately 40x or more. Figure 30 illustrates a chart demonstrating how the combined mass of a concentrator and a PV tile diminishes as a function of

concentration. In particular, the data in the graph is for a 10cm by 10cm power generation tile, with five 1-dimensional Venetian Blinds, a 100 μm cover glass, with 30 um copper back contact/structural support, a 1 μm GaAs photovoltaic film, supported by a 12.5 μm KAPTON polyimide substrate. Thus, it is illustrated how the mass of a corresponding power generation tile can be substantially reduced using concentrators.

[00156] As noted above, the number of junctions within a photovoltaic material also influences the power generation efficiency. Interestingly, Figure 31 depicts that the efficiency of a photovoltaic cell is a stronger function of the number of junctions incorporated than it is of solar radiation concentration. Accordingly, in many instances, photovoltaic materials are implemented that are characterized by multiple junctions are incorporated within a power generation tile.

[00157] In many instances, the contacts used by PV Cells are integrated so as to facilitate the efficiency of the power generation tile. For instance, in many instances, conductive structures that already exist within a power generation tile are used as the conductive contacts of constituent PV Cells. In this way, the conductive structures are made to be dual purpose. For example, in many instances, a Venetian Blinds configuration is implemented that includes a conductive reflector as well as carbon springs for structural support, and the conductive reflector and/or the carbon springs are used as the electrical contacts for the PV Cell. This can be achieved in any of a variety of ways.

[00158] For instance, Figures 32A-32B depict the utilization of a carbon spring and a reflector as the contacts for a corresponding PV Cell in accordance with one instance. In particular, Figure 32A depicts a photovoltaic material 2604 within a Venetian Blind structure that includes carbon springs 2609, a KAPTON polyimide substrate 2607, and a conductive tape bond 2611. Figure 32B illustrates the same structure without the photovoltaic material to indicate that the conductive reflective surface 2605 is exposed and can make direct contact with the utilized photovoltaic material 2604. This geometry can be achieved in any of a variety of ways. For example, that portion of the KAPTON polyimide surface can be excised so that the photovoltaic material can directly contact the conductive reflective surface. Similarly, a conductive tape bond 2611 is used to

couple the opposing side of the photovoltaic material 2604 to a carbon spring. As can be appreciated, the carbon spring 2609 and the reflective surface 2605 can be electrically isolated. Thus, the conductive reflective surface 2605 and the carbon spring 2609 can serve as opposing contacts for the photovoltaic material. In this way, as can be appreciated, each of the reflector 2605 and the carbon spring 2609 can provide multiple functions: (1) the reflector can redirect incident solar radiation onto a photovoltaic material and also serve as a contact for a photovoltaic material; and (2) the carbon spring can allow the Venetian Blind to deploy, provide structural support, and serve as a contact for a photovoltaic material.

[00159] In many instances, a reflector is used to implement the contacts for a PV cell. For example, Figures 33A-33C depict utilizing a reflector to implement the contacts for a photovoltaic material. In particular, Figure 33A illustrates the reflector side of a Venetian Blind structure. More specifically, it is illustrated that the reflector has been bifurcated into two electrically isolated sides, 2705 and 2715. In particular, the underlying KAPTON Polyimide structure 2707 serves to electrically isolate the two sides 2705 and 2715. Figure 33B illustrates the opposing side of the Venetian Blind structure without the photovoltaic material 2704 and the tape bond 2711 to make clear that the photovoltaic material can be electrically connected with each of the two reflective sides 2705 and 2715. Figure 33C illustrates the structure of Figure 33B, except that it further includes the photovoltaic material 2704 and the tape bond 2711. More specifically, the underside of the photovoltaic material 2704 is directly connected to a first side 2715, while the opposing side of the photovoltaic material 2704 is tape bonded to the second side 2705 of the reflective surface. Thus, it is illustrated that a reflective surface can serve a secondary purpose by functioning as the contacts for a PV cell.

[00160] In numerous instances, carbon springs within a power generation tile act as the contacts for a PV cell. For example, Figure 34 illustrates how the carbon springs within a Venetian Blind structure can act as the contacts for a corresponding photovoltaic material. In particular, Figure 34 illustrates a Venetian Blind structure including a photovoltaic material 2804, a KAPTON polyimide substrate 2807, carbon springs 2809, and tape bonding 2811 (the opposing reflective surface is not depicted).

In particular opposing surfaces are of the photovoltaic material 2804 are electrically connected to respective carbon springs 2809 using respective tape bonds 2811, which can thereby function as electrical contacts for the associated photovoltaic material. While several examples of utilizing already existing hardware as electrical contacts for PV cells, it should be clear that the discussed examples are illustrative and are not meant to be comprehensive. For example, while the discussed examples have regarded Venetian Blind configurations, in many instances, Cassegrain configurations and/or Parabolic Trough configurations utilize existing conductive structures to act as electrical contacts. Already existing conductive structures can function as PV cell contacts in any of a variety of ways. Moreover, as can be appreciated, while the implementation of several materials has been discussed, it should be clear that any of a variety of suitable materials can be implemented to construct the described structures.

[00161] To provide context, Figure 35 illustrates how the photovoltaic materials may be interconnected in generating electrical energy. In particular, Figure 35 illustrates how a plurality of Venetian Blind structures can be electrically connected in parallel. Of course, it should be clear that the photovoltaic materials can be adjoined in any suitable way in. For example, in many instances, the photovoltaic materials are connected in series.

[00162] While the above descriptions have largely regarded suitable Space-based Solar Power Systems that can benefit from the incorporation of the described mirrors, it should be clear that the previously described mirrors can be implemented in any of a variety of apparatus. Additionally, while specific mirror structures have been discussed, mirrors can be incorporated in any of a variety of ways in accordance w/ many embodiments of the invention. More generally, while particular embodiments and applications of the present invention have been illustrated and described herein, it is to be understood that the invention is not limited to the precise construction and components disclosed herein and that various modifications, changes, and variations may be made in the arrangement, operation, and details of the methods and apparatuses of the present invention without departing from the spirit and scope of the invention as it is defined in the appended claims.

WHAT IS CLAIMED IS:

1. A space-based solar power system comprising:
a photovoltaic material; and
a mirror that is – relative to a 10 μm thick sheet of aluminum – more transparent to at least one of a substantial portion of the microwave region of the electromagnetic spectrum and a substantial portion of the radio wave region of the electromagnetic spectrum;
wherein the mirror is configured to focus incident visible light onto the photovoltaic material.

2. The space-based solar power system of claim 1, wherein the mirror comprises alternating layers of high refraction index materials and low refraction index materials.

3. The space-based solar power system of claim 2, wherein the alternating layers of high refraction index and low refraction index materials are disposed on a polymer membrane.

4. The space-based solar power system of claim 2, wherein a plurality of the high refraction index materials comprise the same material, and a plurality of the low refraction index materials comprise the same material.

5. The space-based solar power system of claim 2, wherein the alternating layers of high refraction index and low refraction index materials are configured such that incident light reflects off of the constituent interfaces and thereby constructively interferes to achieve reflection.

6. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, and wherein the mirror comprises at least 72 pairs.

7. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, and wherein the mirror comprises at least 144 pairs.

8. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, and wherein at least two of the pairs comprise different materials.

9. The space-based solar power system of claim 8, wherein the different pairs each give rise to different reflectivity profiles.

10. The space-based solar power system of claim 9, wherein at least two reflectivity profiles are characterized by a reflectance % of greater than 90% for at least some region within the visible light portion of the electromagnetic spectrum.

11. The space-based solar power system of claim 2, wherein at least one layer that includes a low index refraction material comprises one of: MgF_2 and SiO_2.

12. The space-based solar power system of claim 2, wherein at least one layer that includes a high index refraction material comprises one of: Diamond, AlN, and Ta_2O_5.

13. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, and at least one pair comprises Diamond and MgF_2 adjacently disposed.

14. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, wherein the mirror includes at least 72 pairs, and wherein each of the pairs comprises Diamond and MgF_2 adjacently disposed.

15. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, wherein the mirror includes at least 144 pairs, and wherein each of the pairs comprises Diamond and MgF_2 adjacently disposed.

16. The space-based solar power system of claim 2, wherein the thickness of the mirror is between approximately 1 μm and approximately 10 μm.

17. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, and at least one pair comprises AlN and SiO_2 adjacently disposed.

18. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, and at least one pair comprises Diamond and SiO_2 adjacently disposed.

19. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, and at least one pair comprises AlN and MgF_2 adjacently disposed.

20. The space-based solar power system of claim 2, wherein adjacent high refraction index and low refraction index materials define a pair, and at least one pair comprises Ta_2O_5 and MgF_2 adjacently disposed.

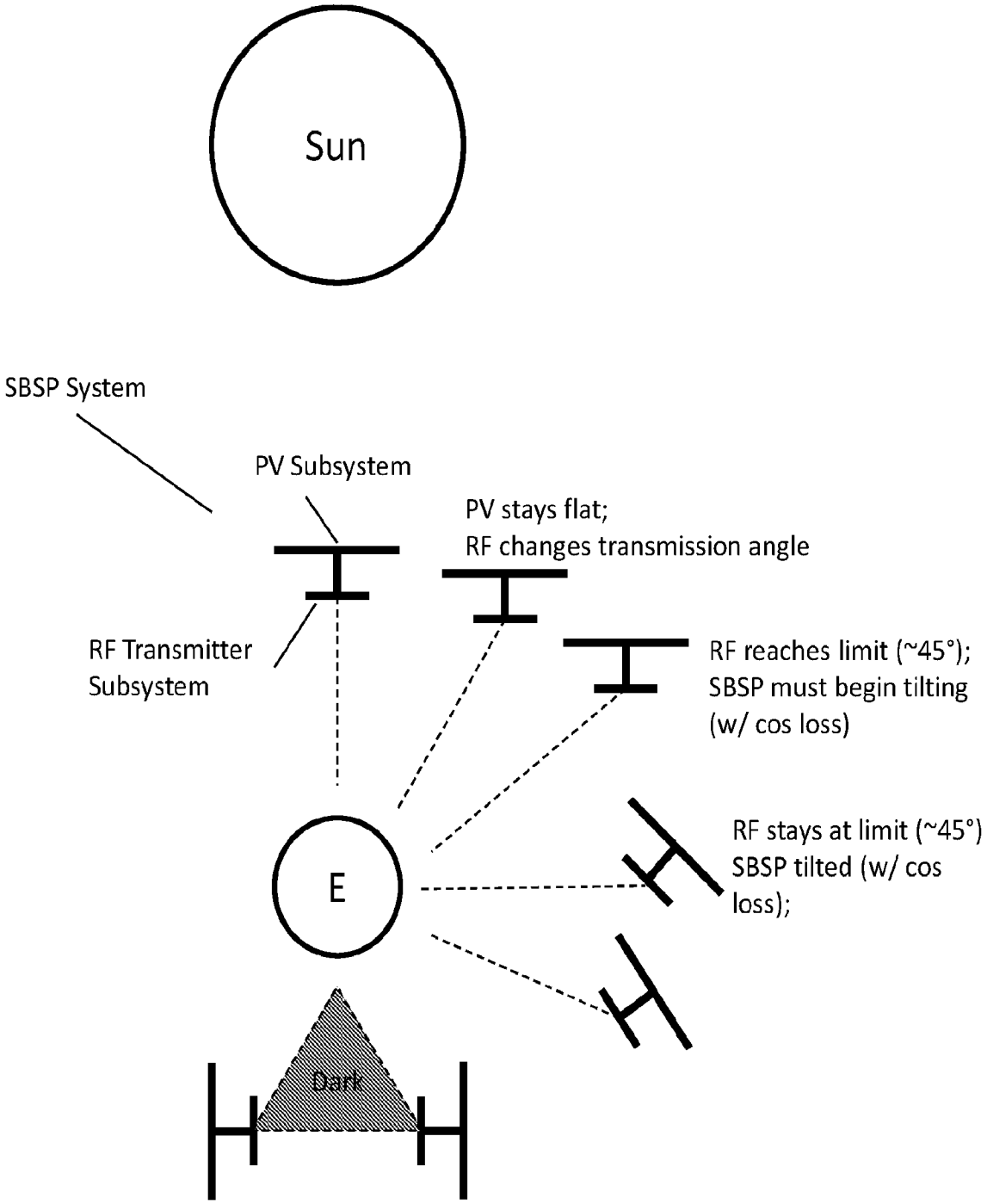

Sun
SBSP System
PV Subsystem
PV stays flat;
RF changes transmission angle
RF Transmitter
Subsystem
RF reaches limit (~45°);
SBSP must begin tilting
(w/ cos loss)
RF stays at limit (~45°)
SBSP tilted (w/ cos
loss);
E
Dark

FIG. 1A

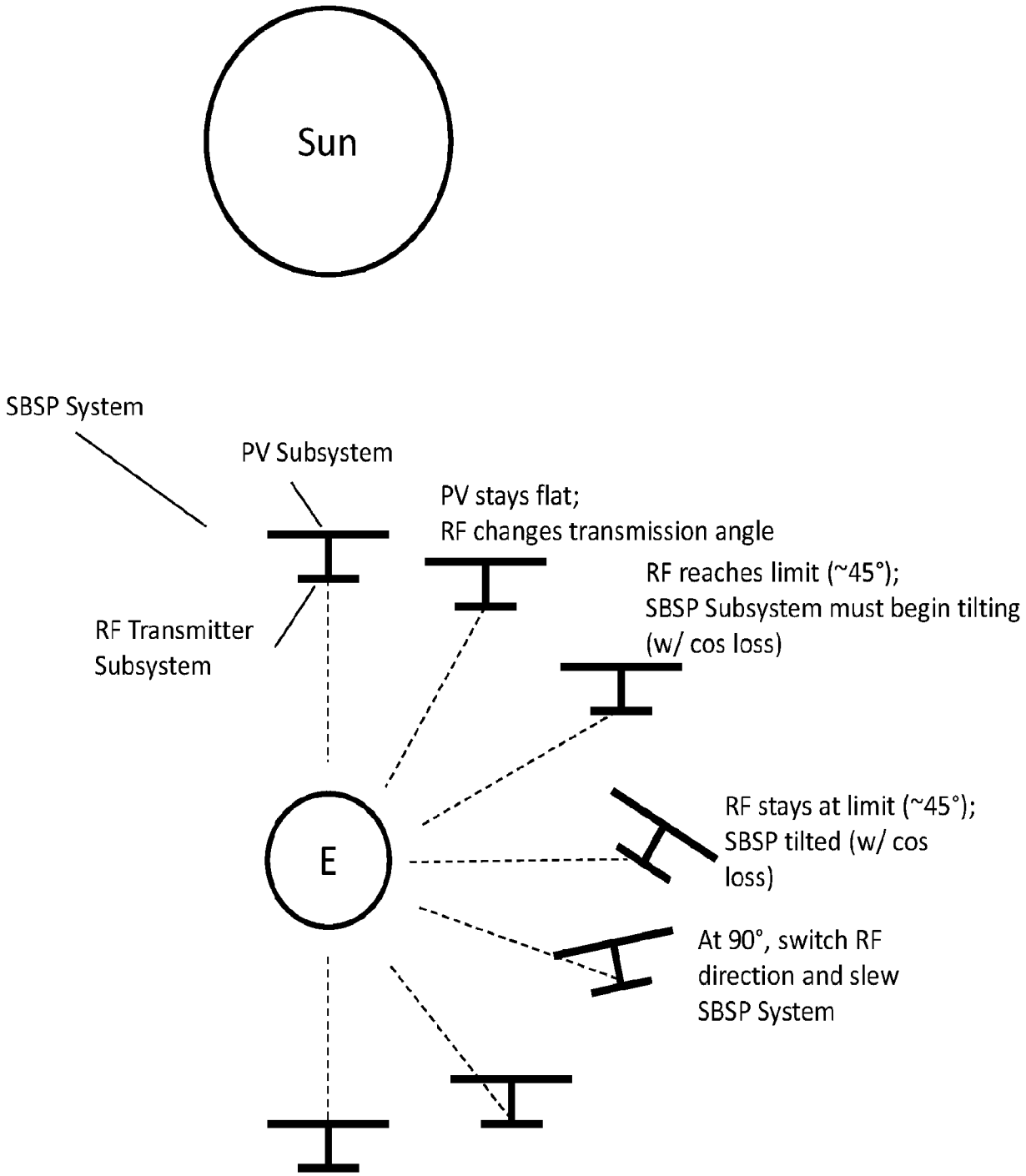

Sun
SBSP System
PV Subsystem
PV stays flat;
RF changes transmission angle
RF reaches limit (~45°);
SBSP Subsystem must begin tilting
(w/ cos loss)
RF Transmitter
Subsystem
RF stays at limit (~45°);
SBSP tilted (w/ cos
loss)
E
At 90°, switch RF
direction and slew
SBSP System

FIG. 1B

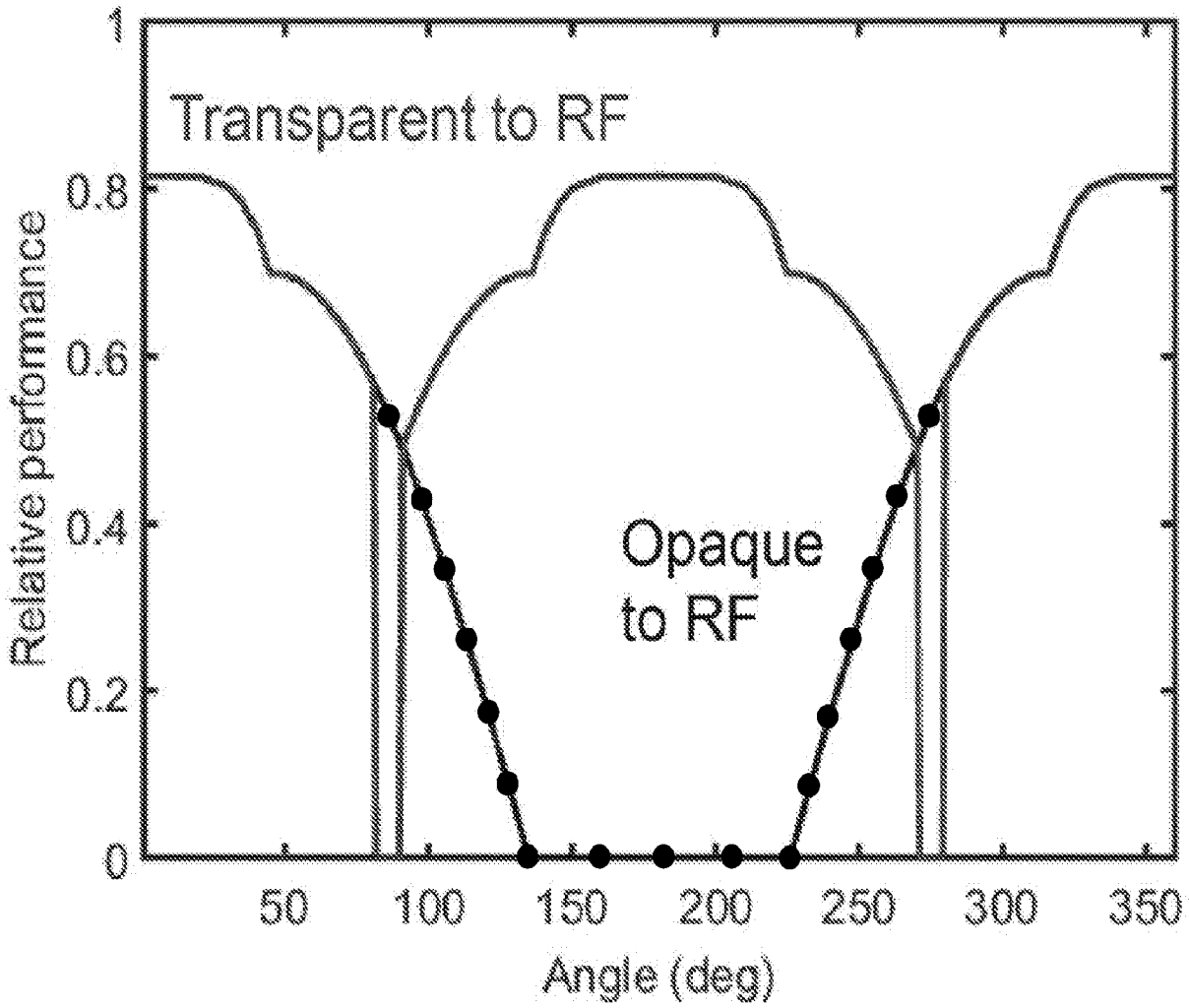

Transparent to RF
Opaque
to RF
Relative performance
Angle (deg)
0
0.2
0.4
0.6
0.8
1
50
100
150
200
250
300
350

FIG. 1C

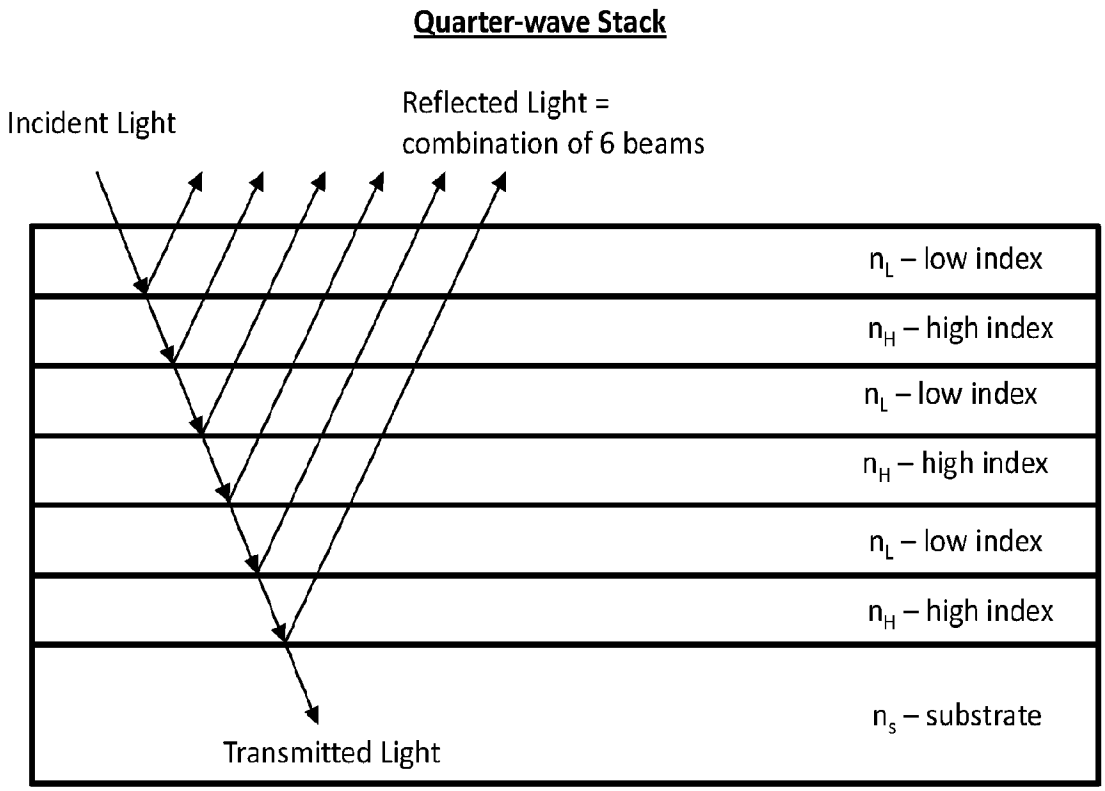

Quarter-wave Stack
Incident Light
Reflected Light =
combination of 6 beams
n_L – low index
n_H – high index
n_L – low index
n_H – high index
n_L – low index
n_H – high index
n_s – substrate
Transmitted Light

FIG. 2A

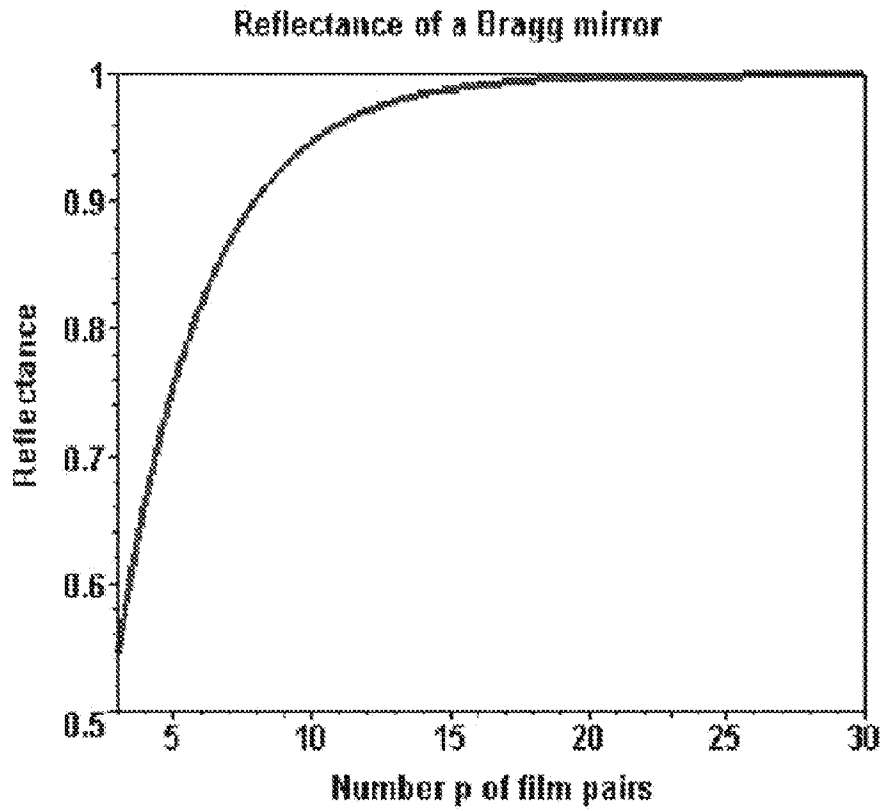

Reflectance of a Bragg mirror
Reflectance
1
0.9
0.8
0.7
0.6
0.5
5
10
15
20
25
30
Number p of film pairs

FIG. 2B

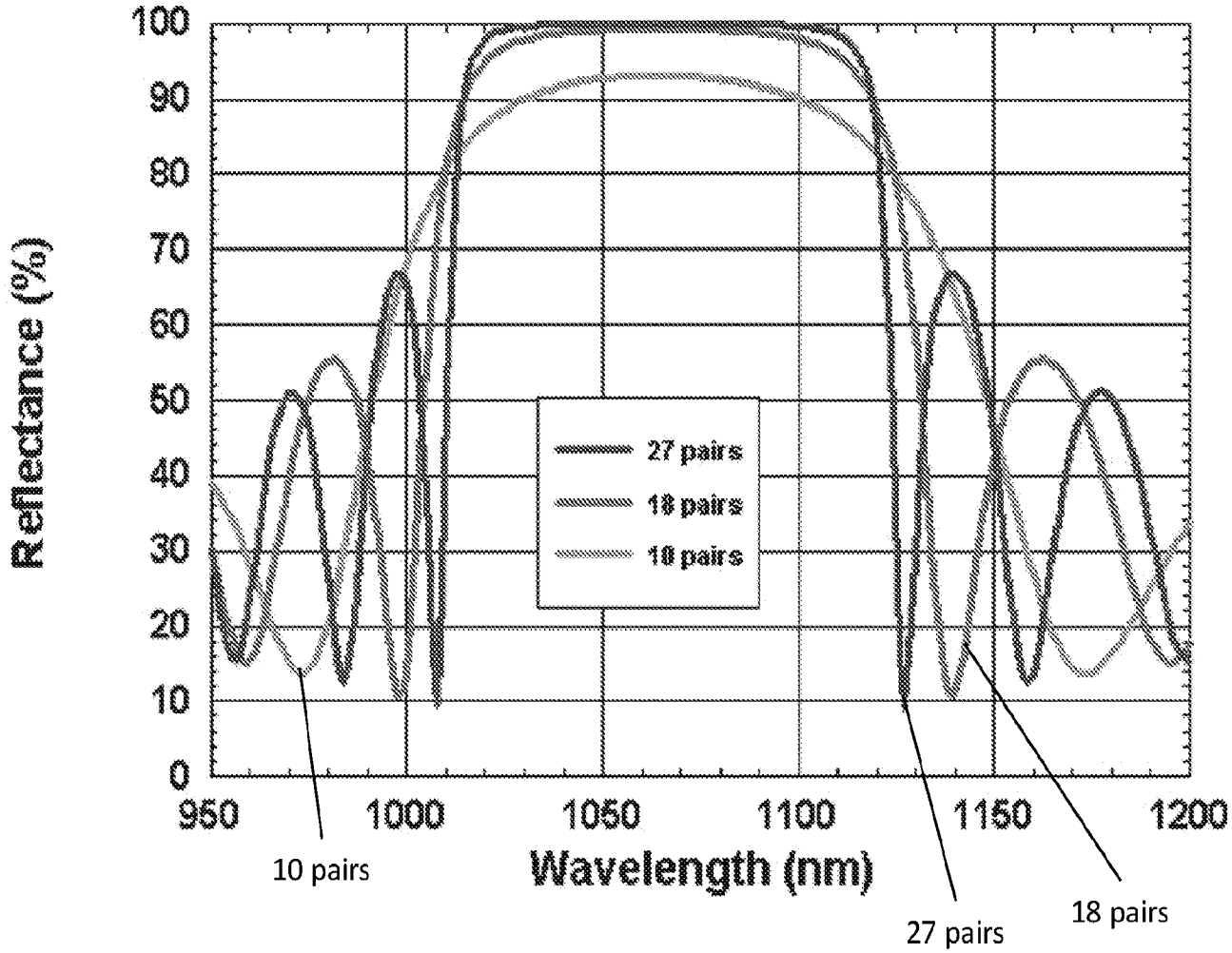

Reflectance (%)
100
90
80
70
60
50
40
30
20
10
0
950
1000
1050
1100
1150
1200
Wavelength (nm)
27 pairs
18 pairs
10 pairs
10 pairs
27 pairs
18 pairs

FIG. 3

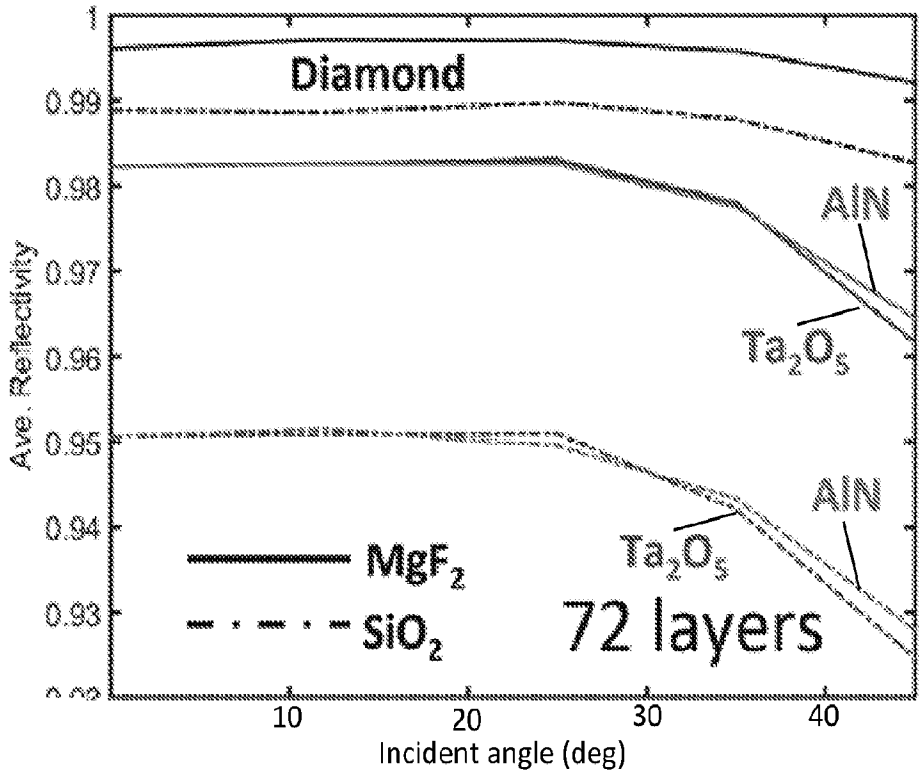

Diamond
AlN
Ta_2O_5
AlN
Ta_2O_5
MgF_2
SiO_2
72 layers
Ave. Reflectivity
Incident angle (deg)
1
0.99
0.98
0.97
0.96
0.95
0.94
0.93
10
20
30
40

FIG. 4A

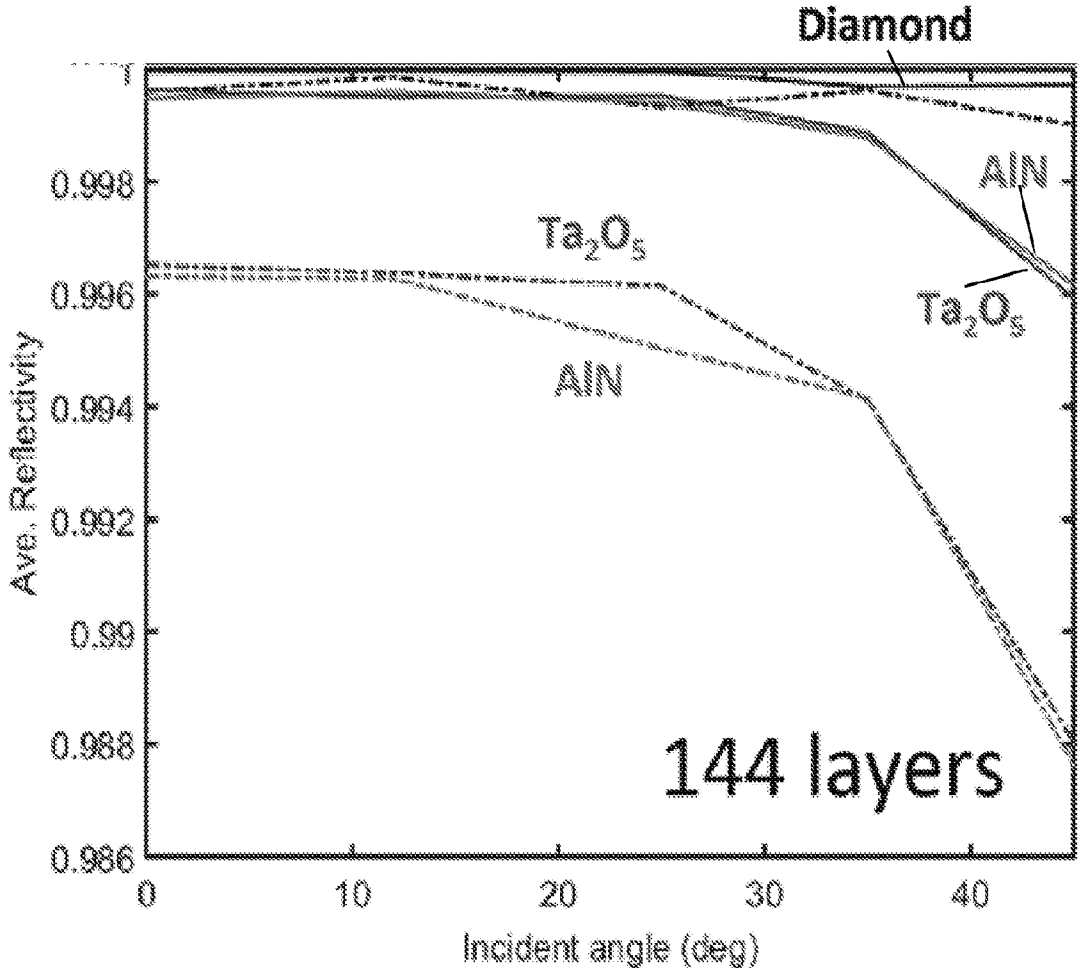

Diamond
AlN
Ta_2O_5
Ta_2O_5
AlN
144 layers
Ave. Reflectivity
Incident angle (deg)
1
0.998
0.996
0.994
0.992
0.99
0.988
0.986
0
10
20
30
40

FIG. 4B

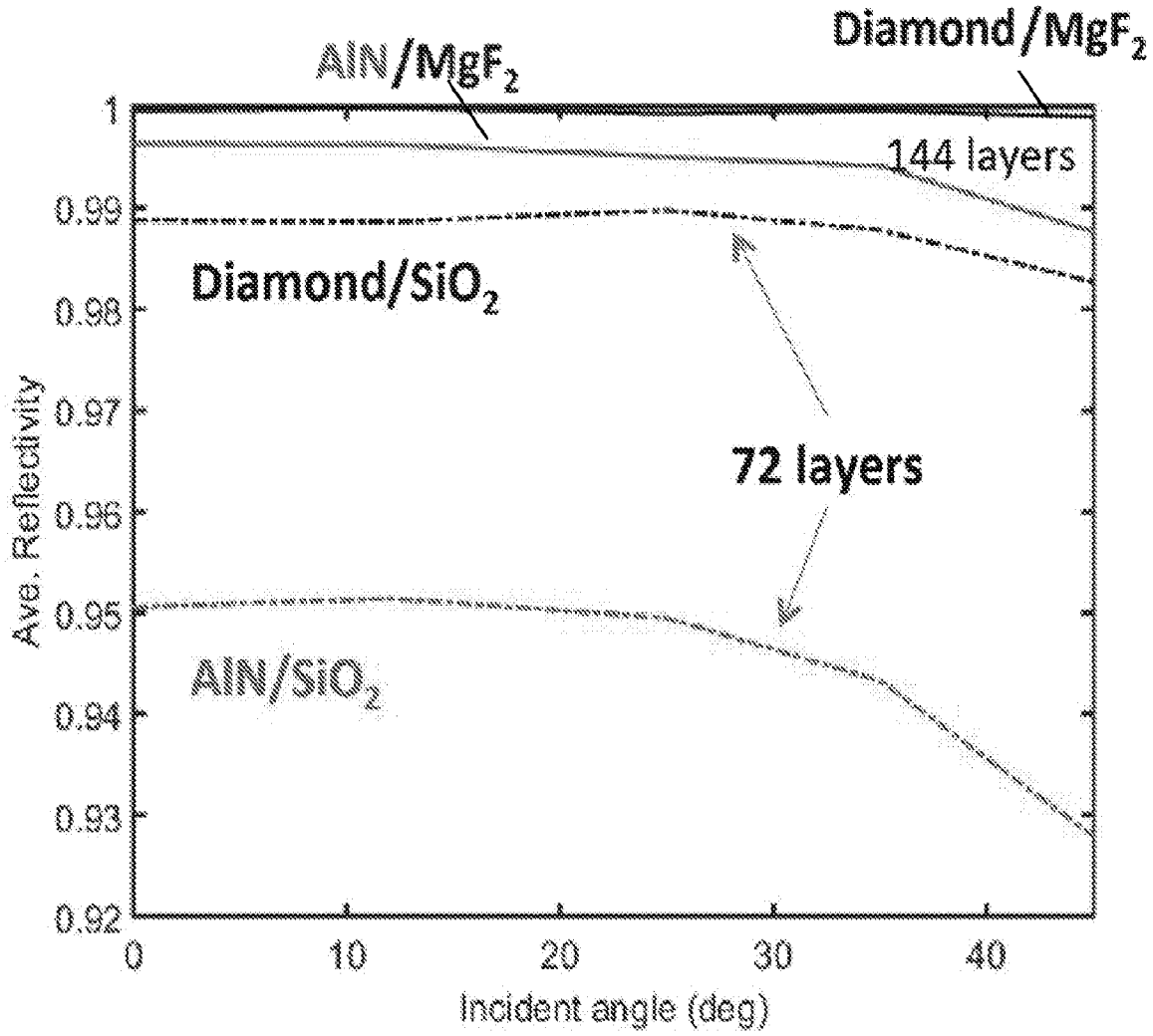

AlN/MgF2
Diamond/MgF2
144 layers
Diamond/SiO2
72 layers
AlN/SiO2
Ave. Reflectivity
1
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0
10
20
30
40
Incident angle (deg)

FIG. 4C

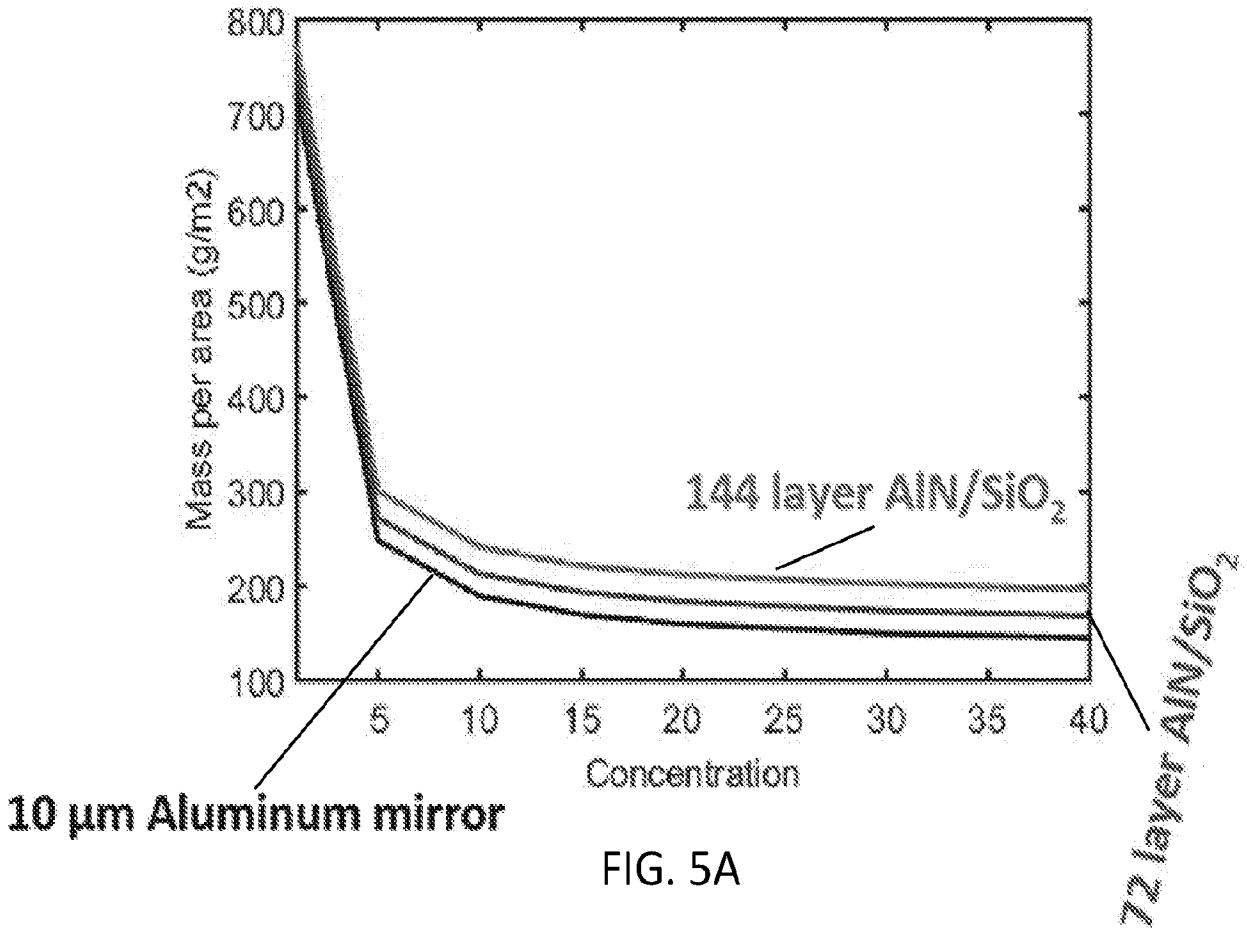

800
700
600
500
400
300
200
100
Mass per area (g/m2)
5
10
15
20
25
30
35
40
Concentration
144 layer AlN/SiO2
72 layer AlN/SiO2
10 µm Aluminum mirror

FIG. 5A

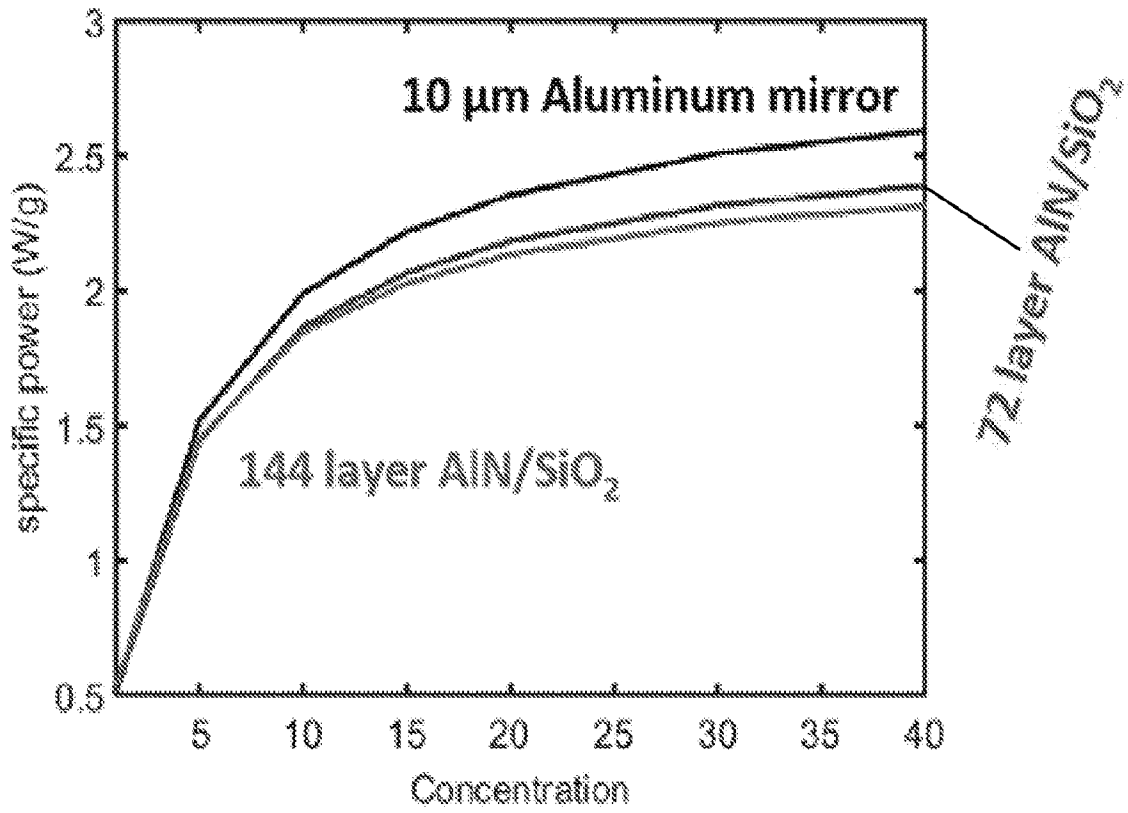

3
2.5
2
1.5
1
0.5
specific power (W/g)
5
10
15
20
25
30
35
40
Concentration
10 µm Aluminum mirror
144 layer AlN/SiO2
72 layer AlN/SiO2

FIG. 5B

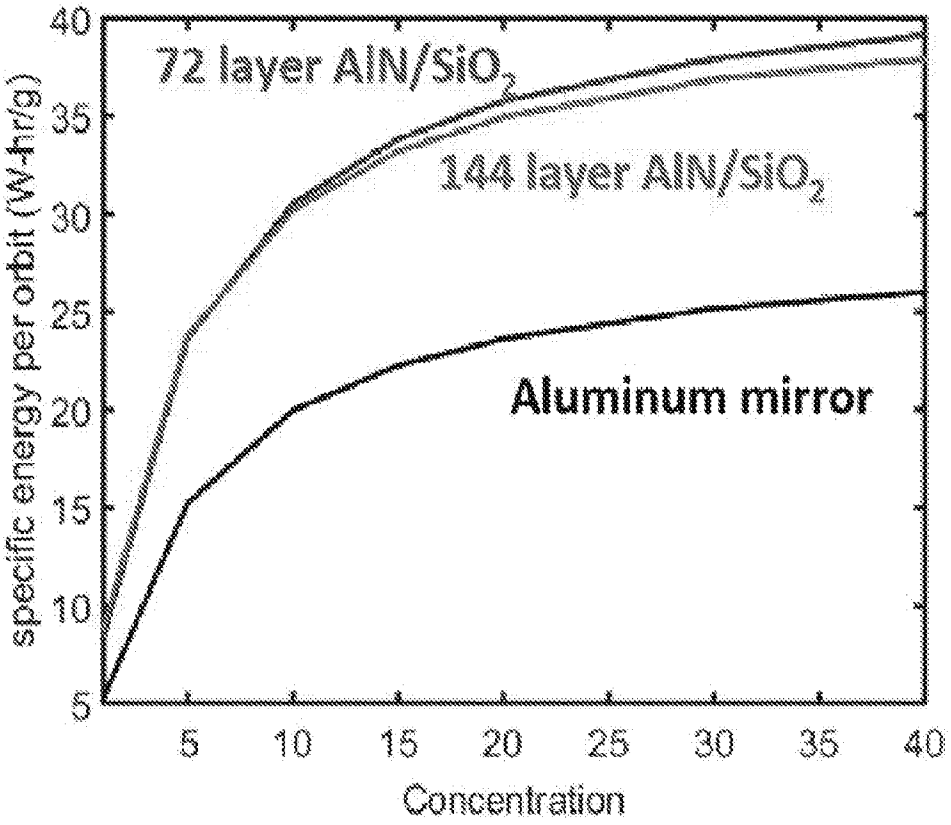

72 layer AlN/SiO2
144 layer AlN/SiO2
Aluminum mirror
specific energy per orbit (W-hr/g)
Concentration
40
35
30
25
20
15
10
5
5
10
15
20
25
30
35
40

FIG. 6

FIG. 7

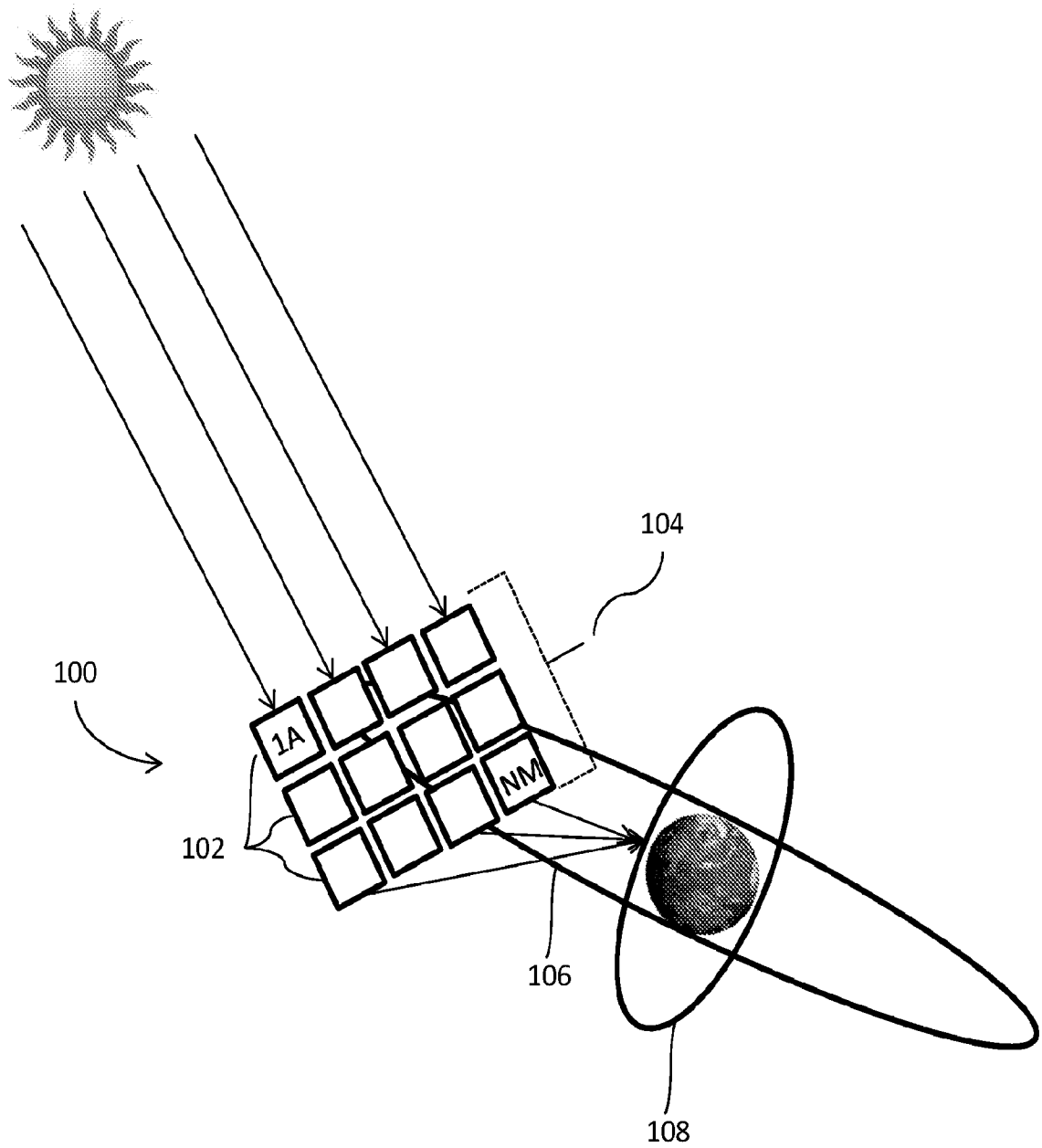


FIG. 8

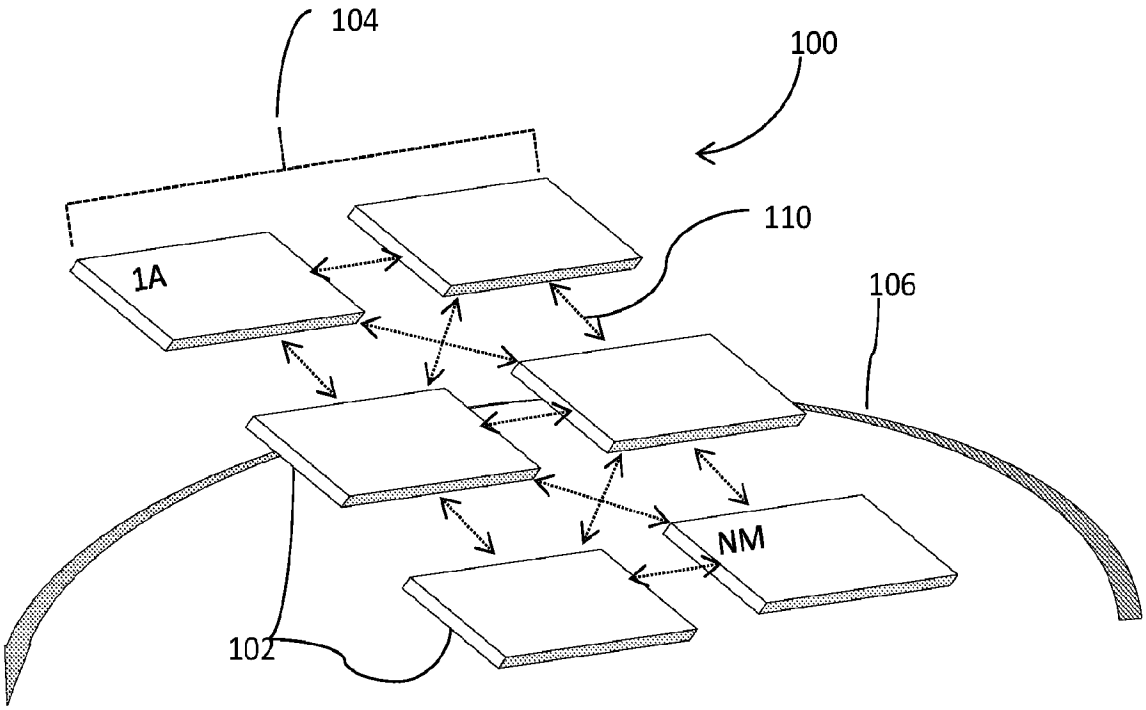


FIG. 9

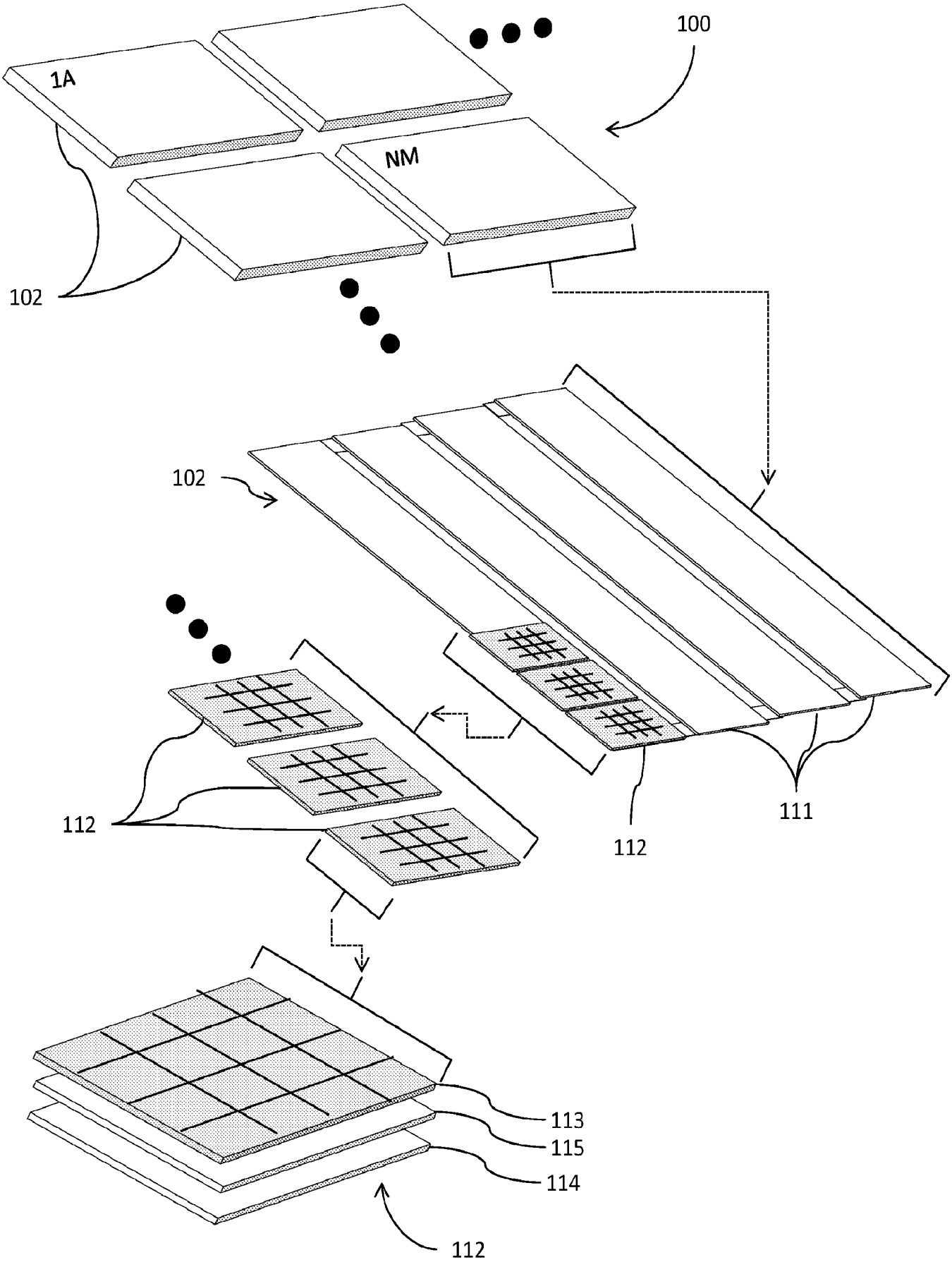
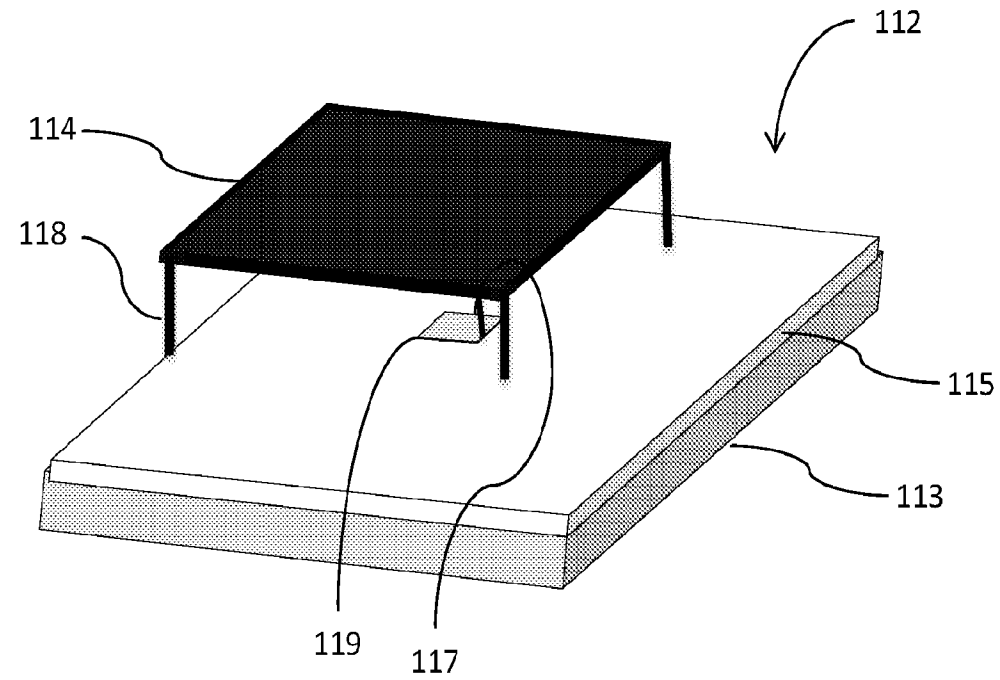


FIG. 10a



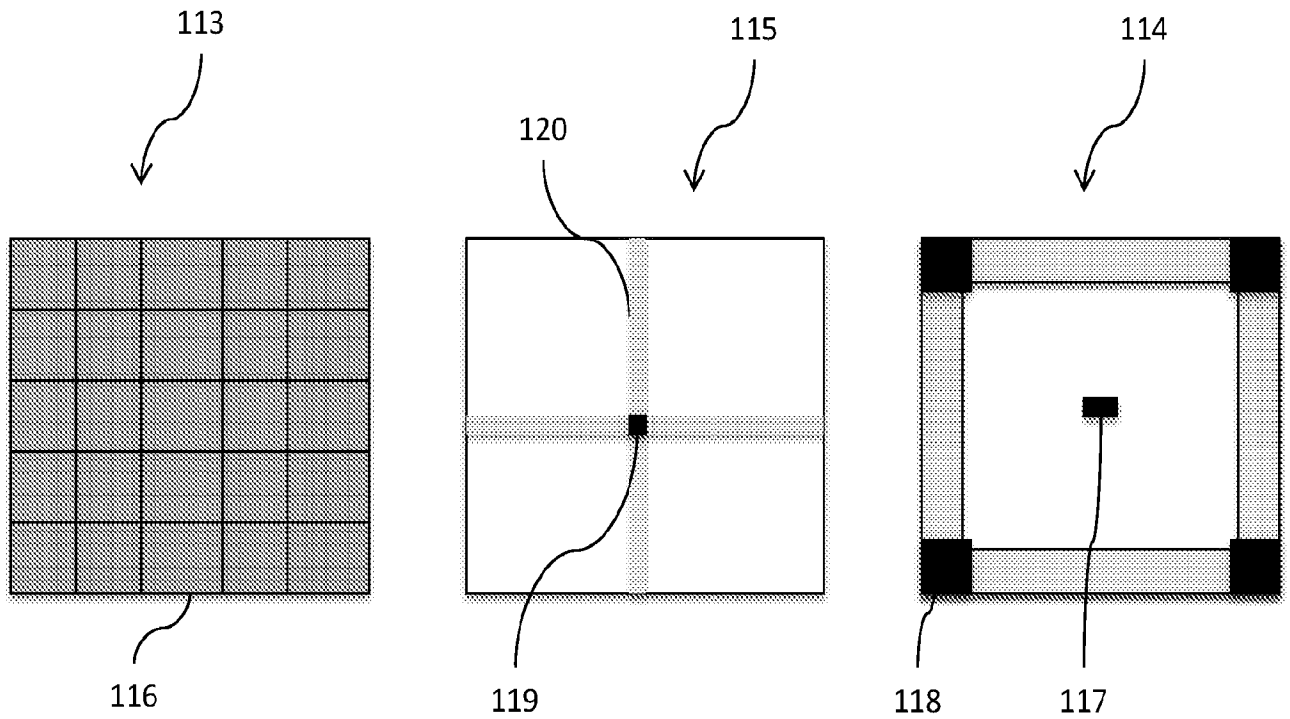


FIG. 10b

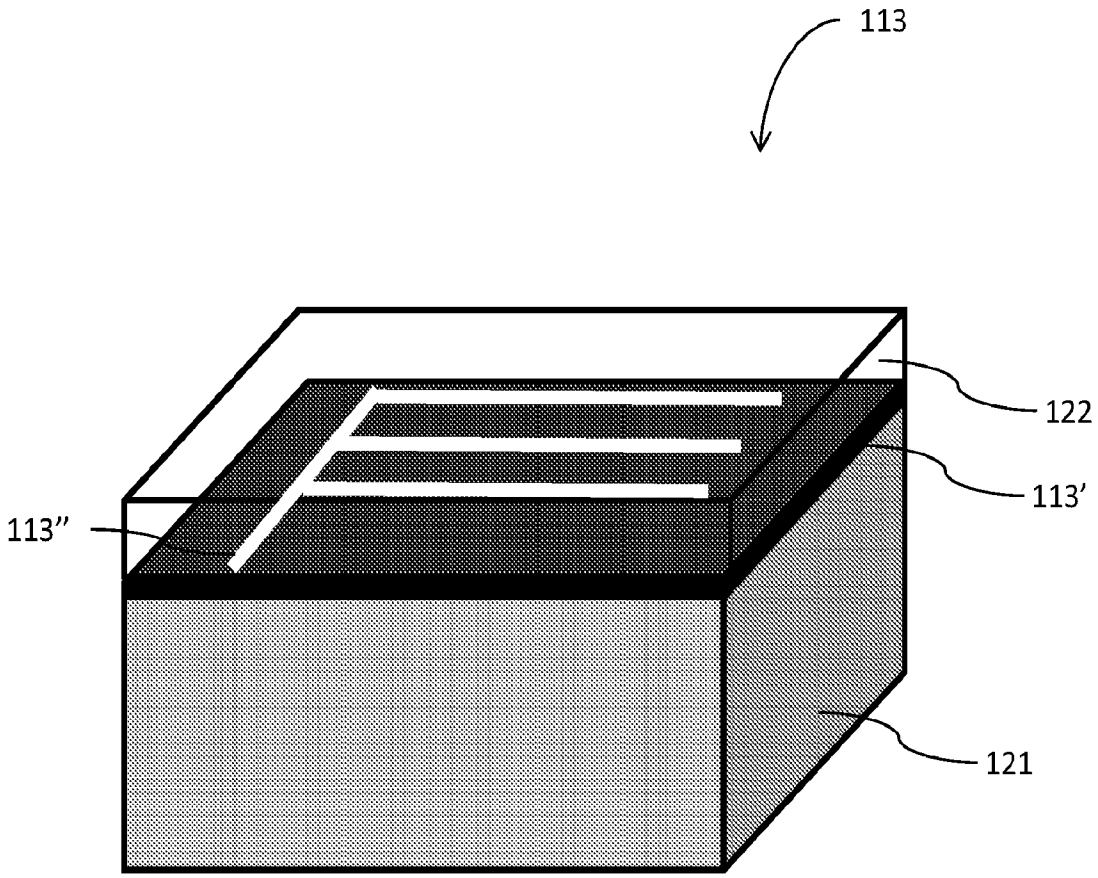


FIG. 10c

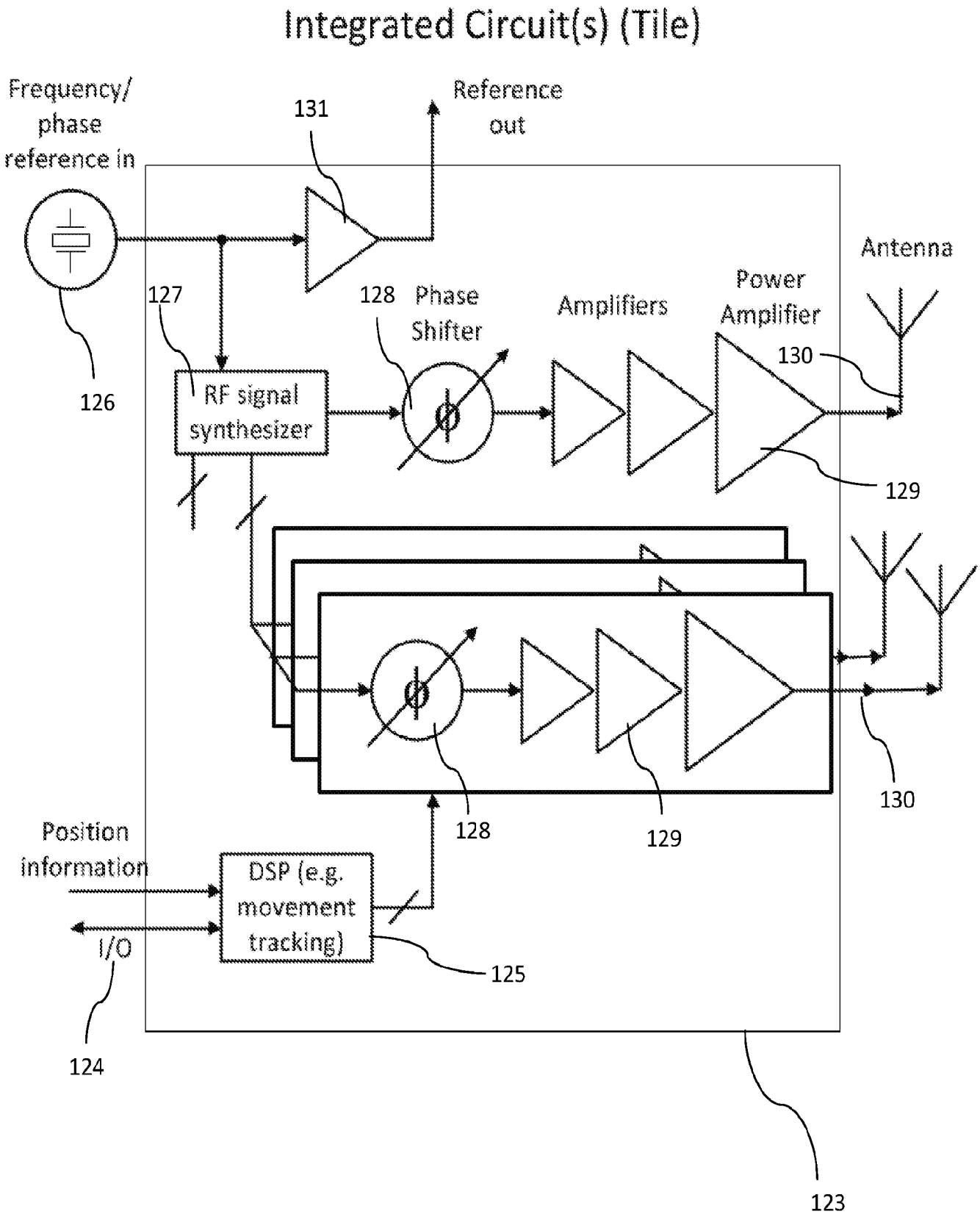

Integrated Circuit(s) (Tile)
Frequency/ phase reference in
131
Reference out
Antenna
127
128
Phase Shifter
Amplifiers
Power Amplifier
130
126
RF signal synthesizer
129
130
128
129
Position information
DSP (e.g. movement tracking)
I/O
125
124
123

FIG. 11

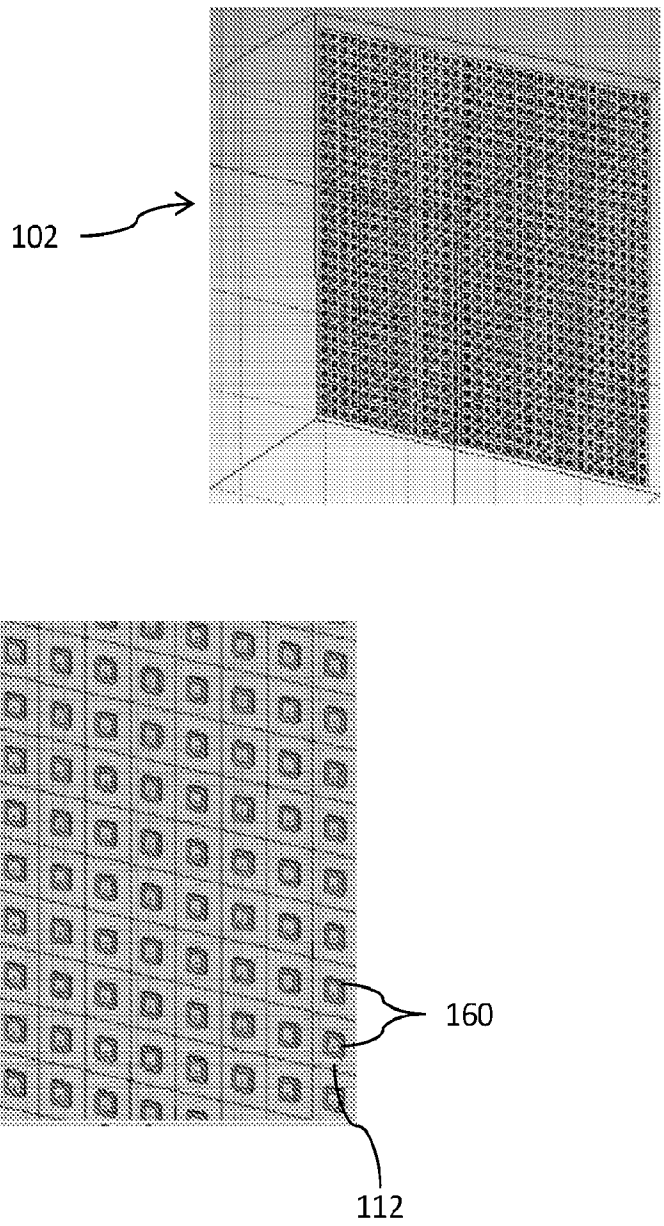


FIG. 12

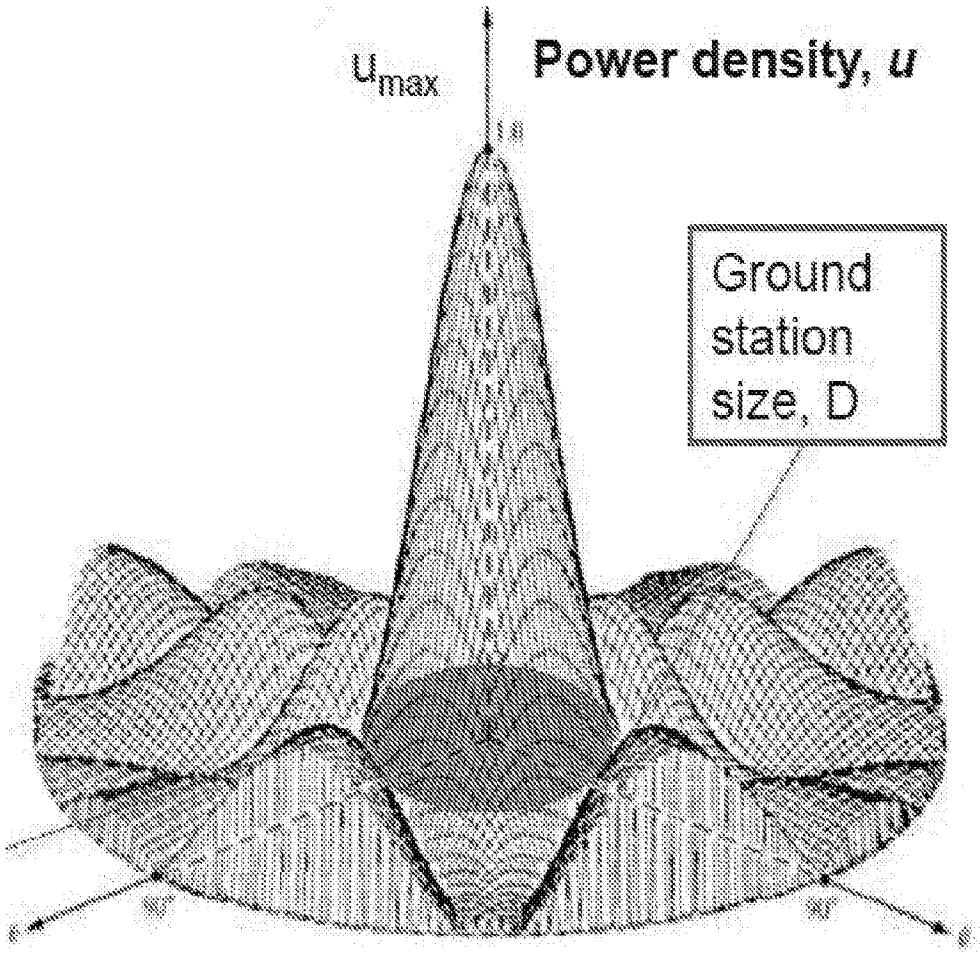


FIG. 13

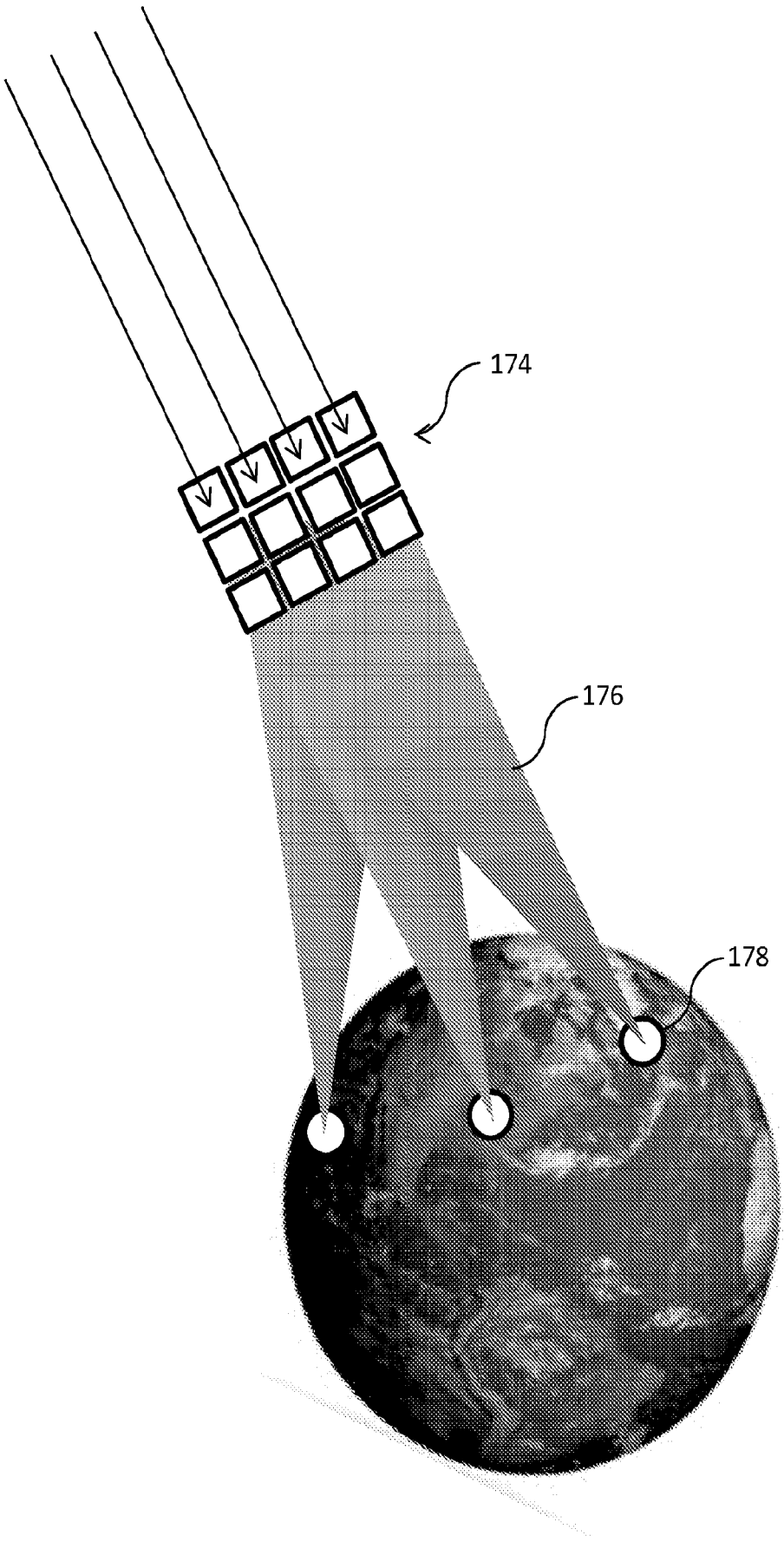


FIG. 14a

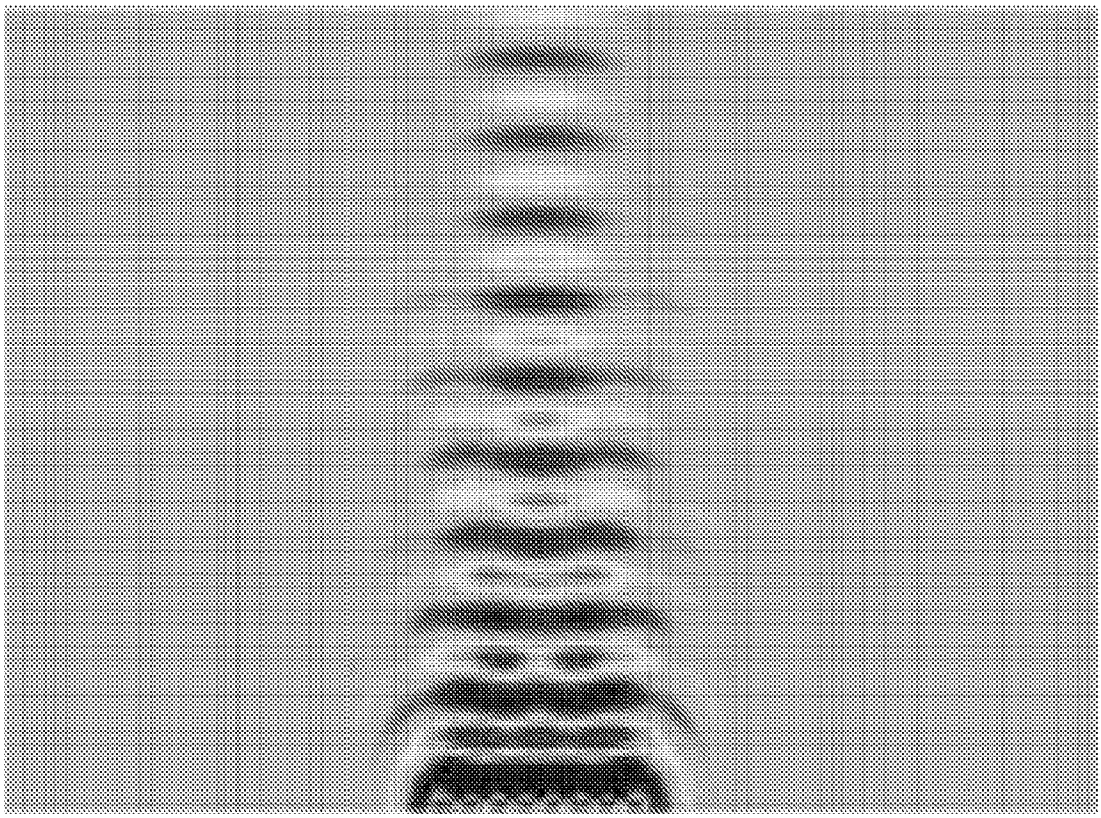


FIG. 14b

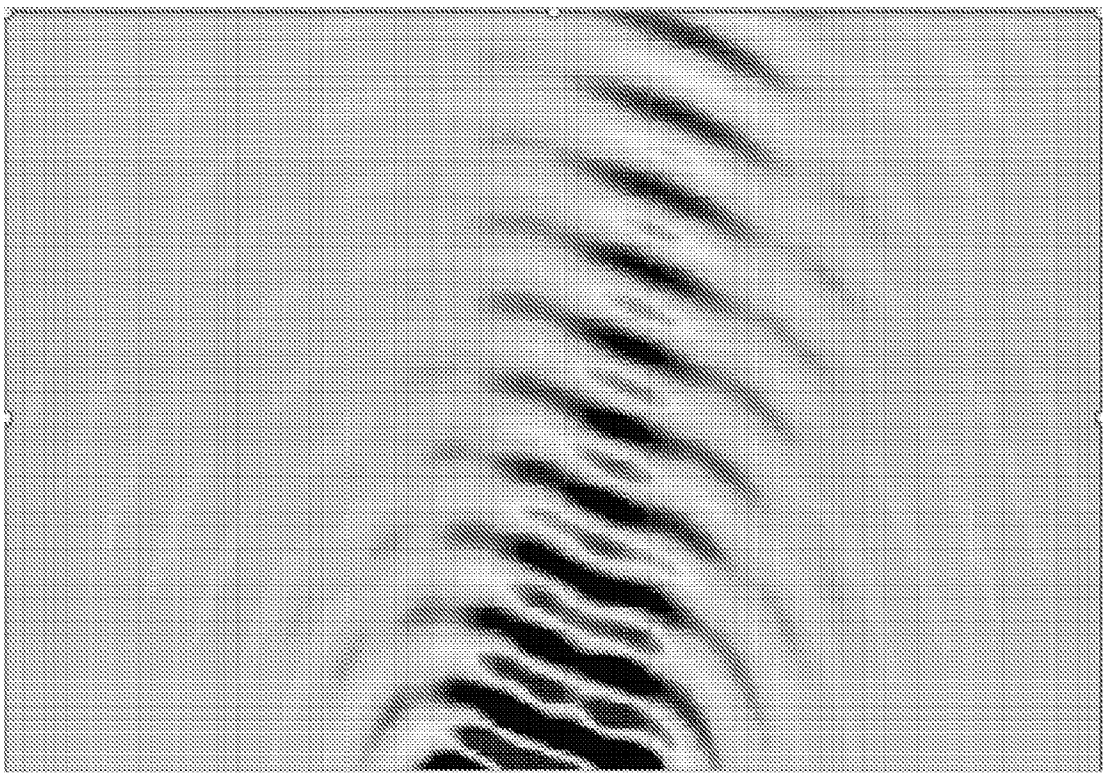


FIG. 15a

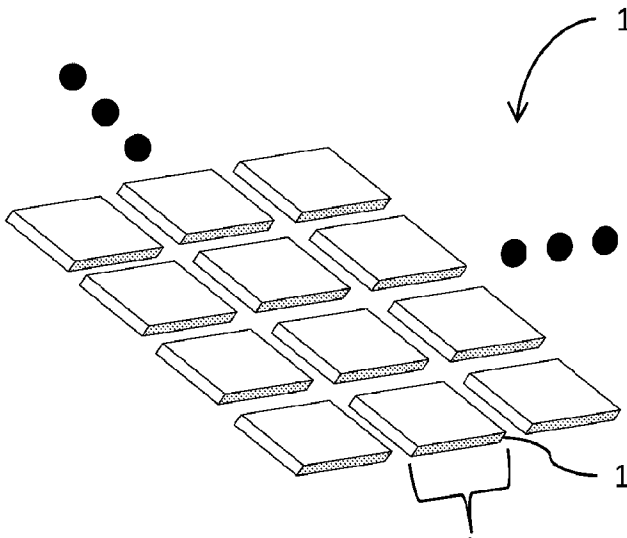
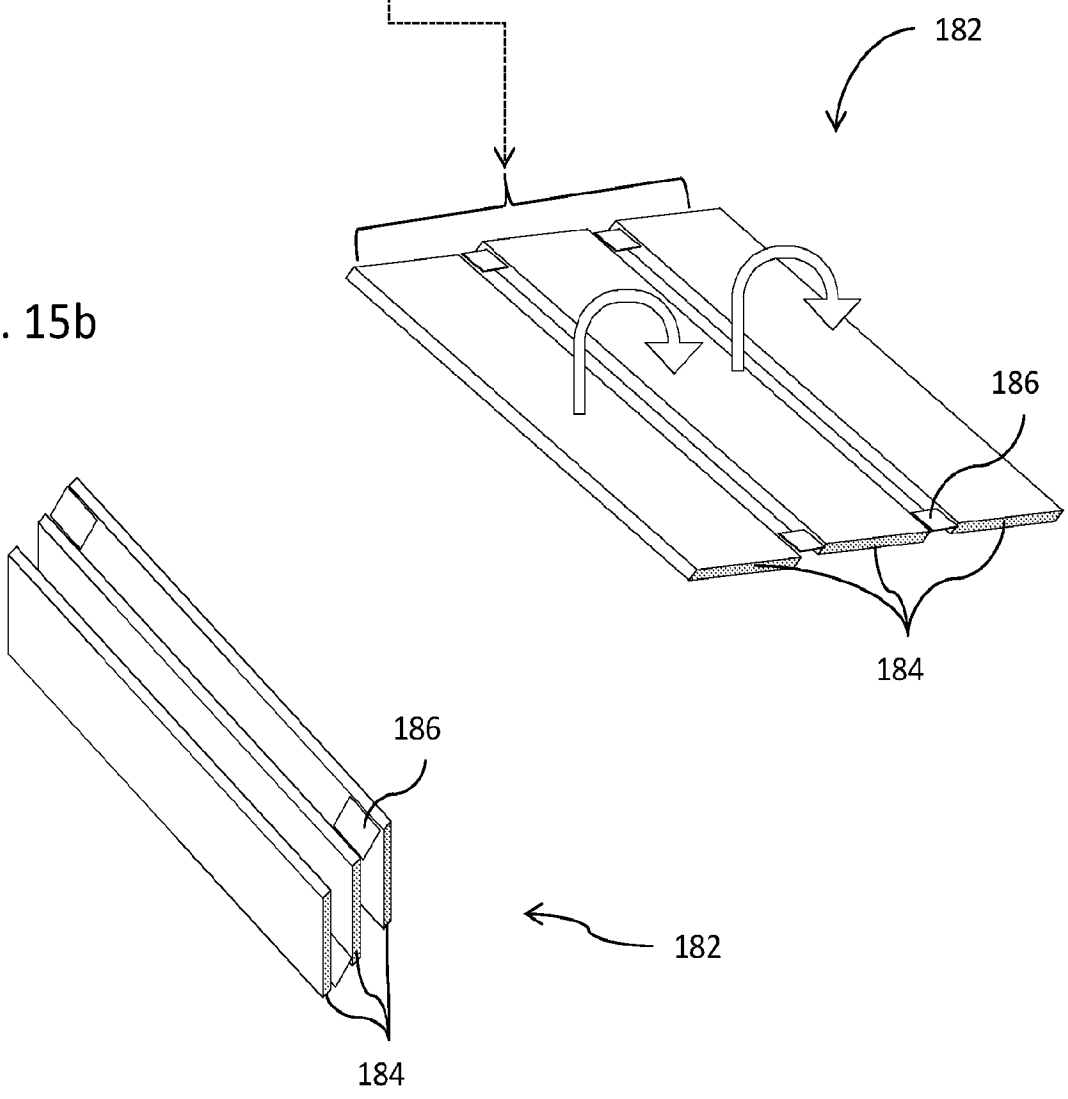


FIG. 15b



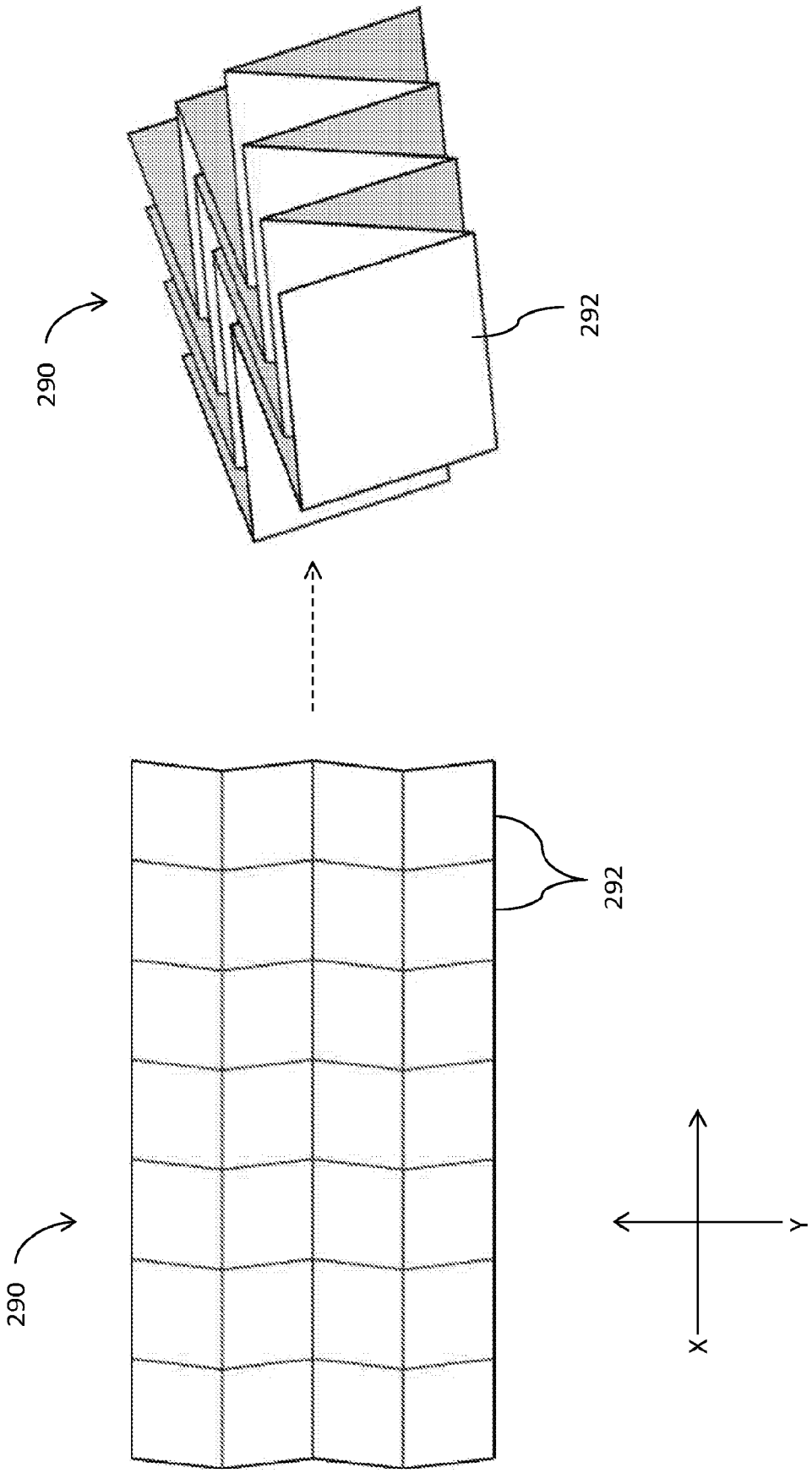


FIG. 16

FIG. 17

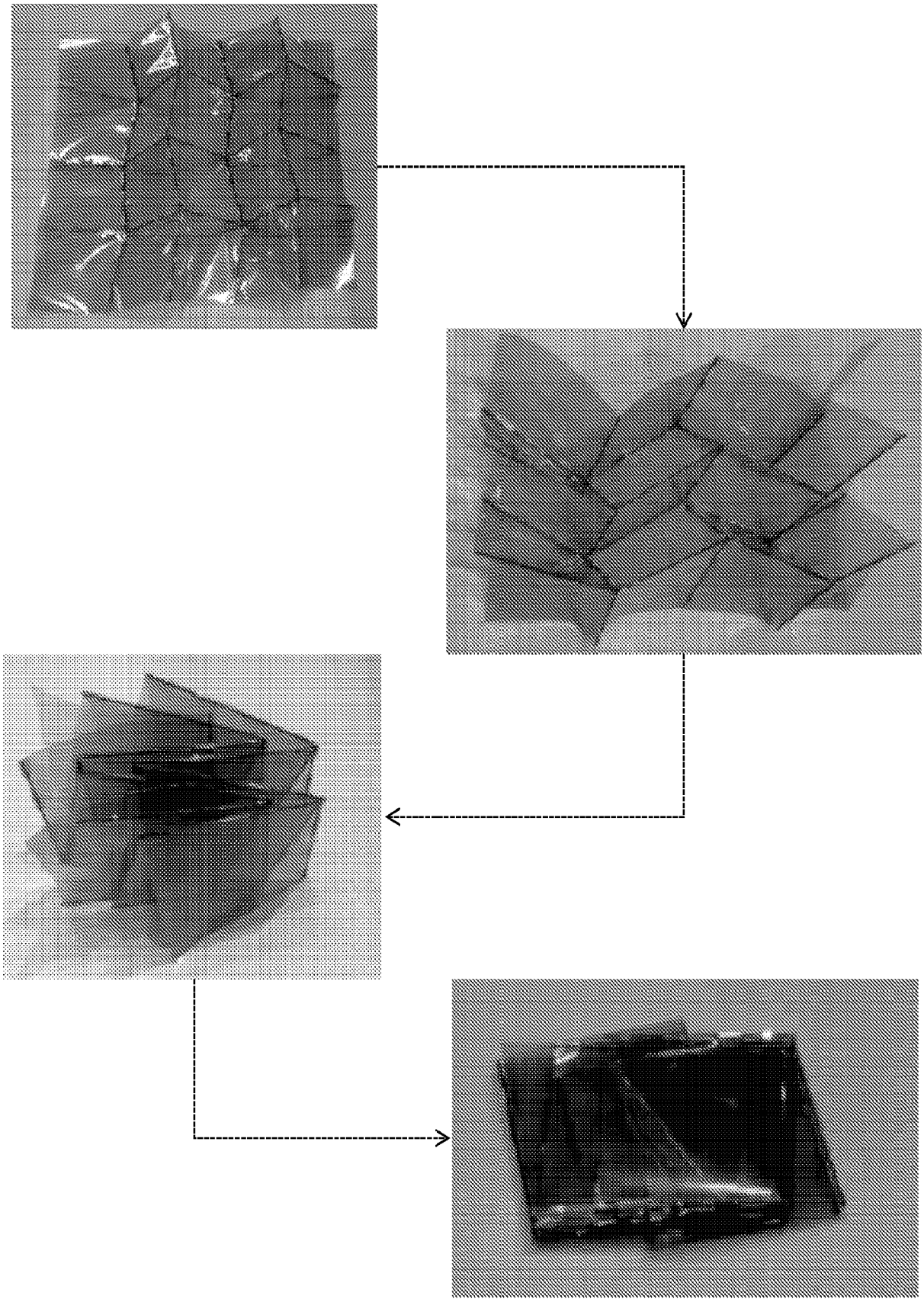


FIG. 18a

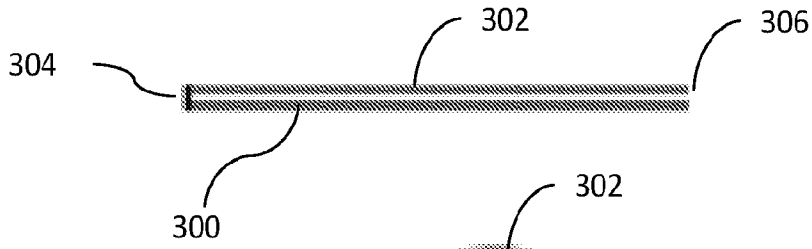


FIG. 18b

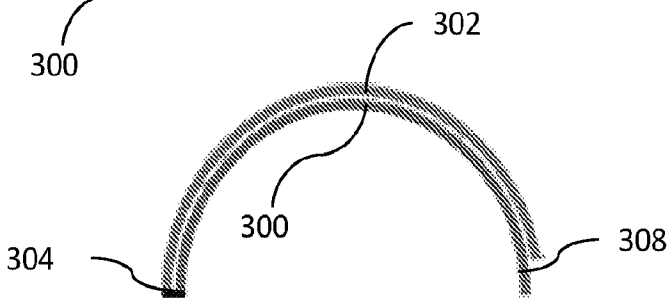


FIG. 18c

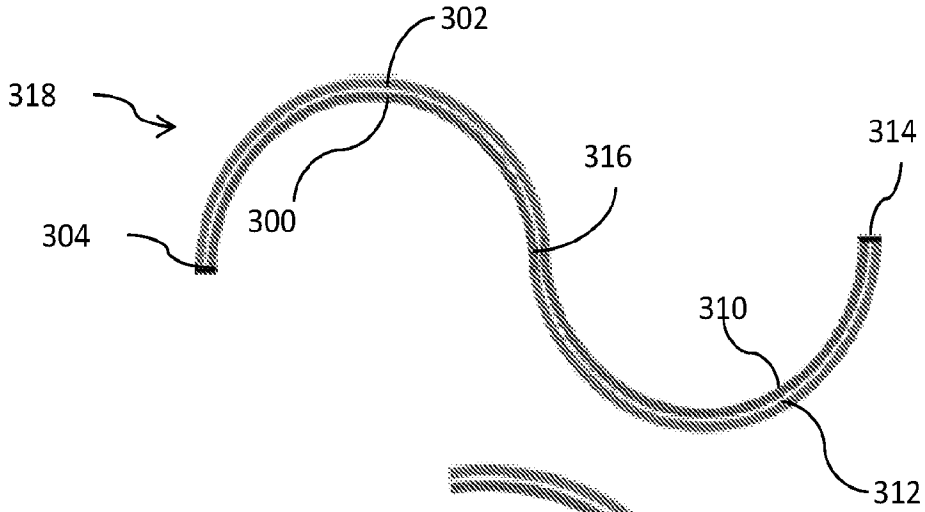
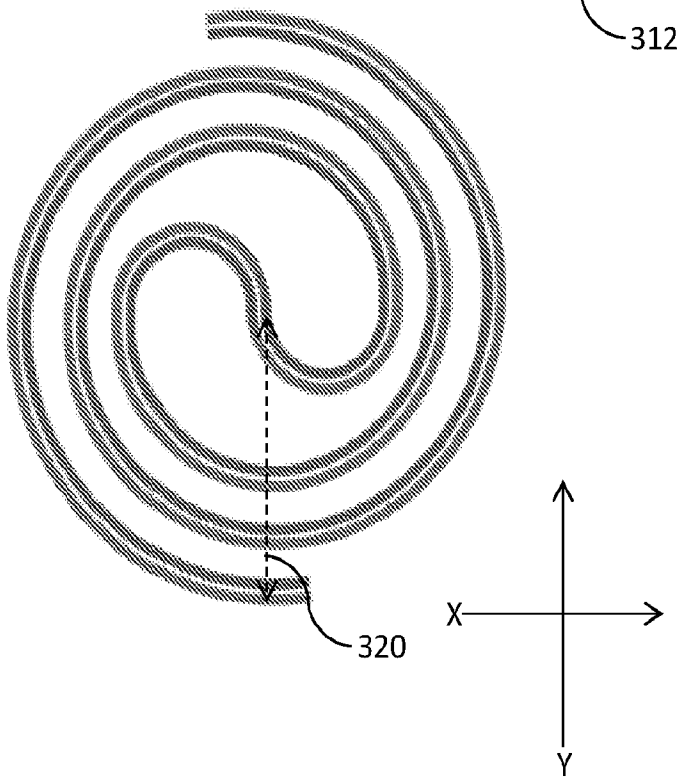


FIG. 18d



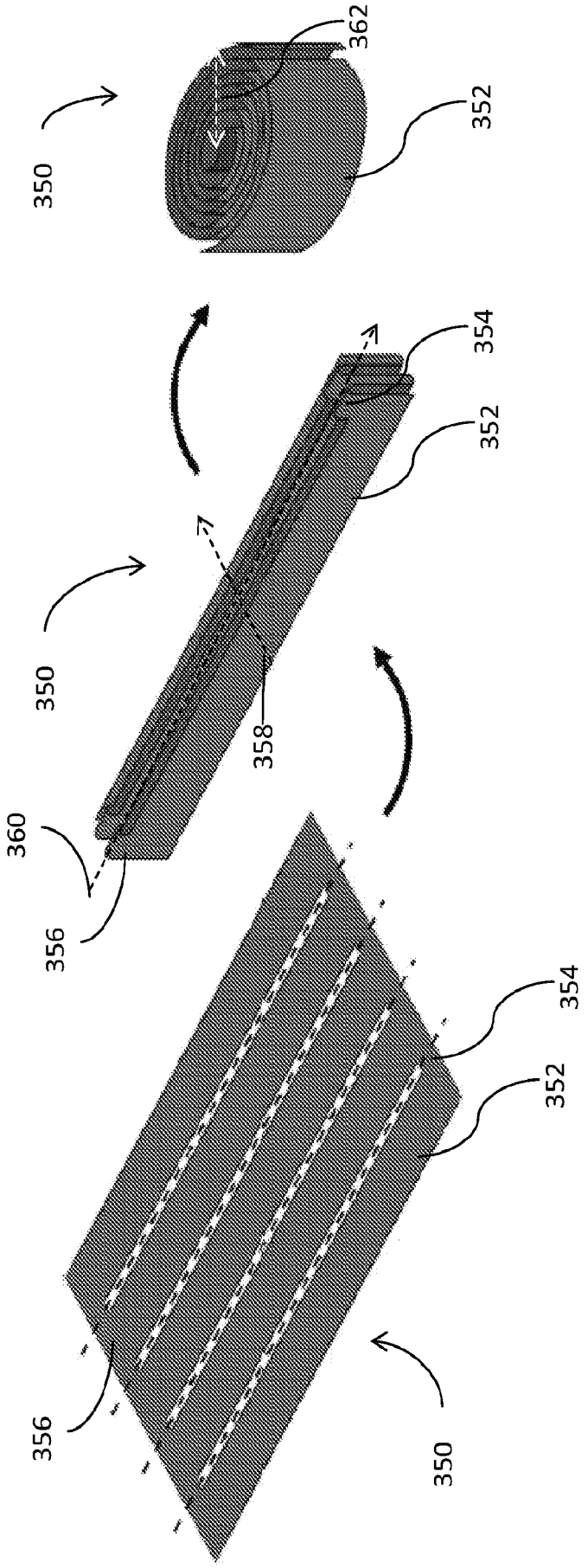


FIG. 19

FIG. 20

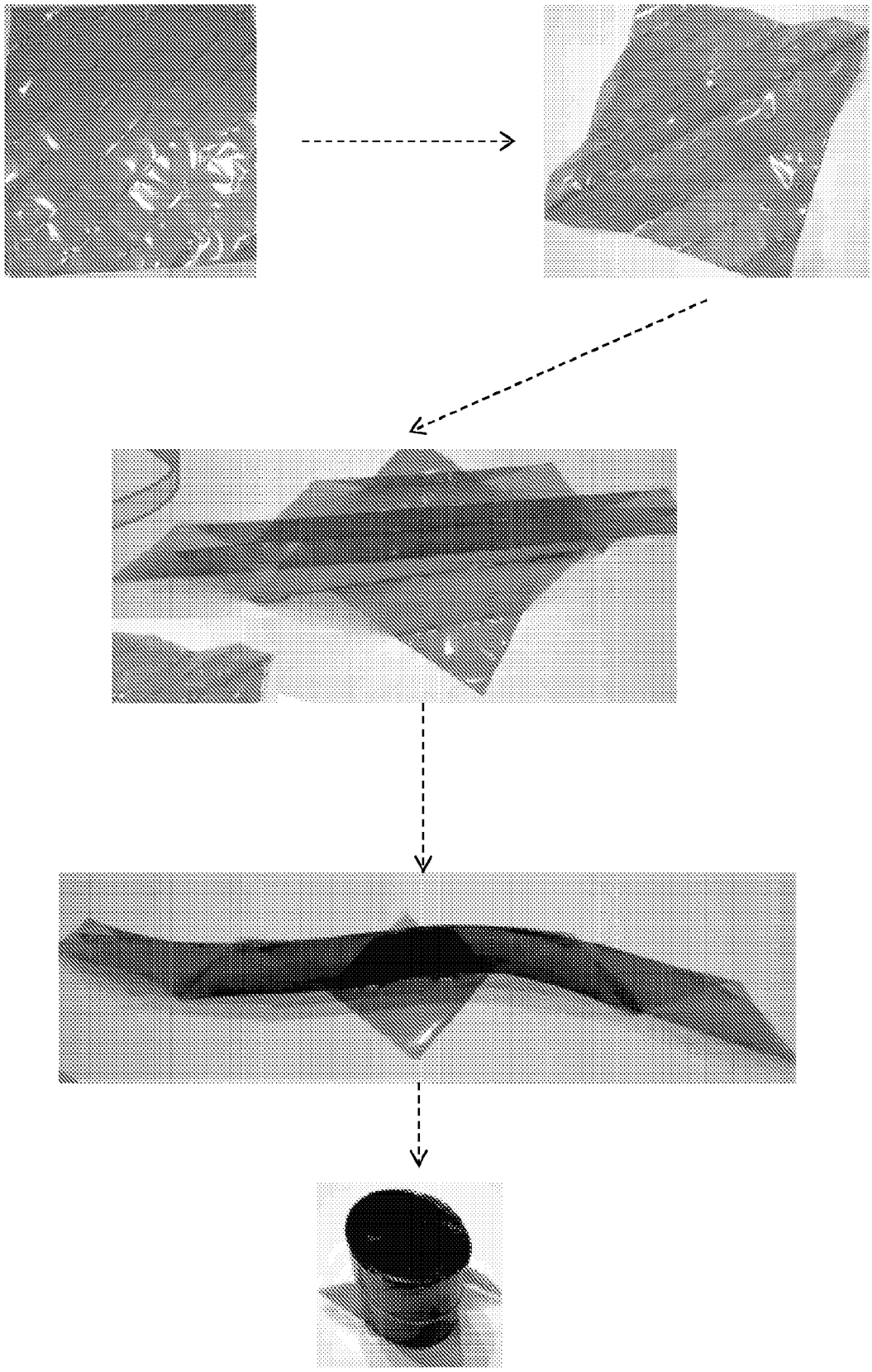


FIG. 21

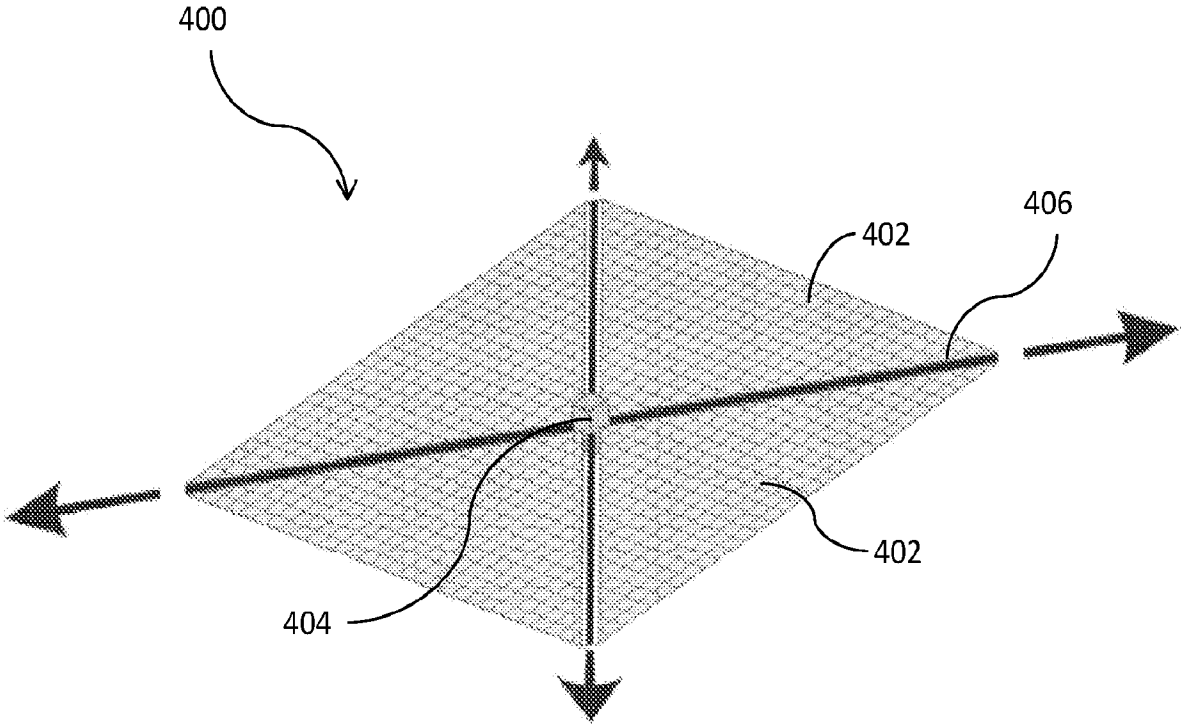
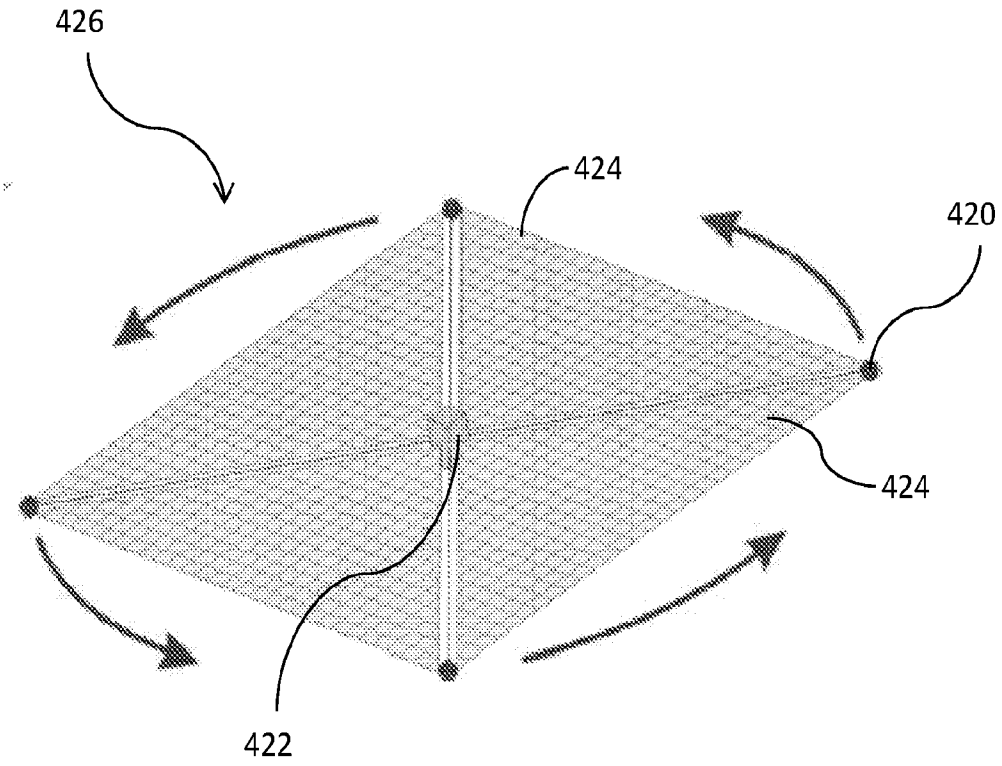


FIG. 22



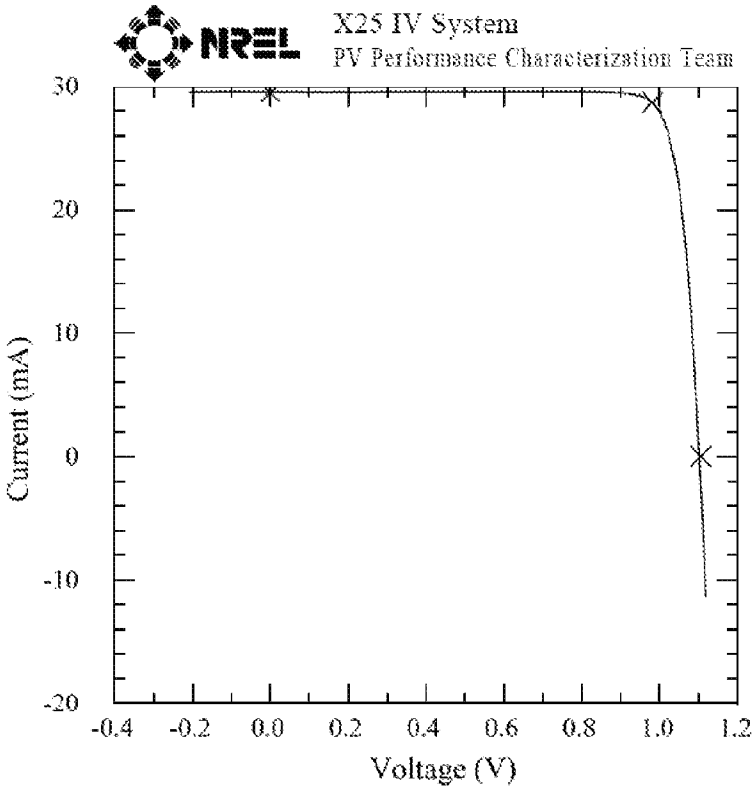


FIG. 23A

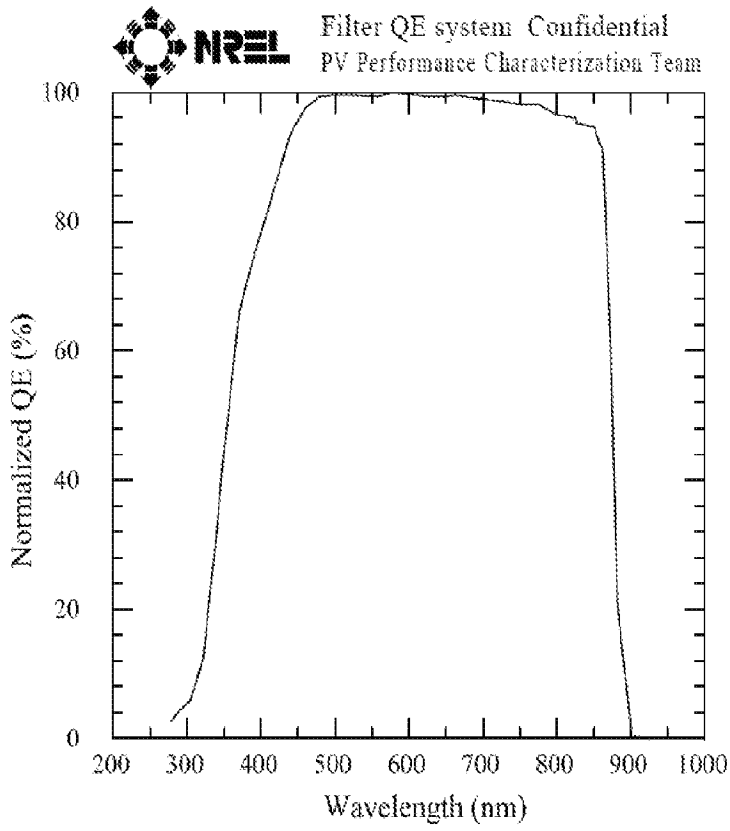


FIG. 23B

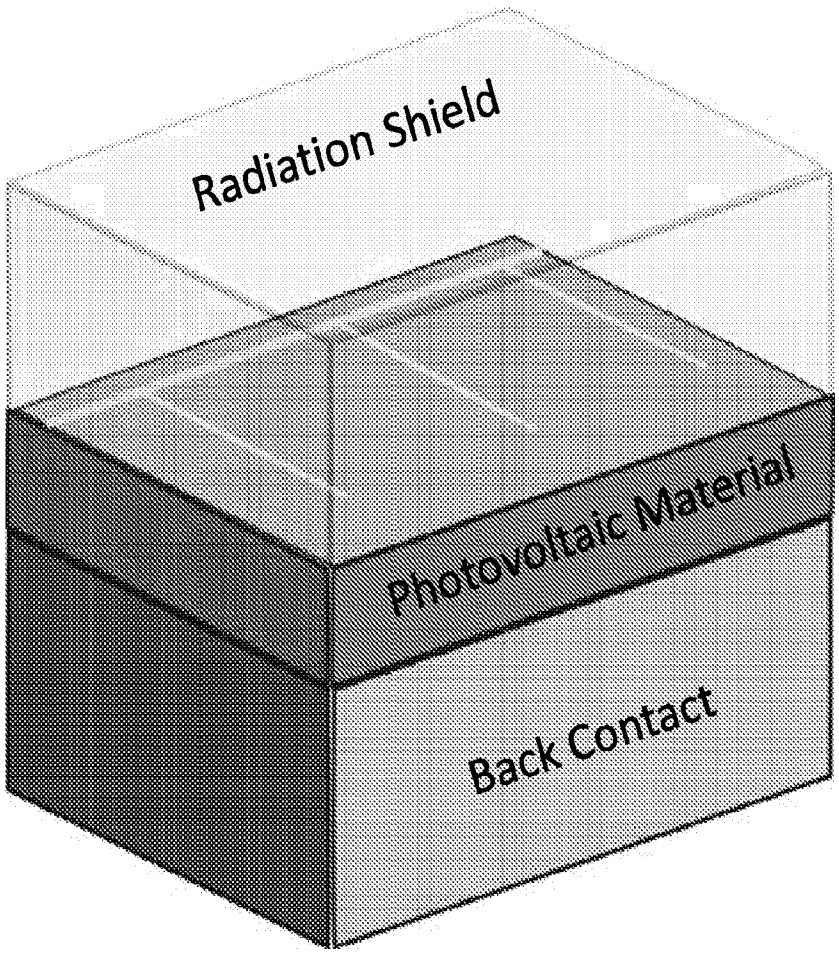


FIG. 24

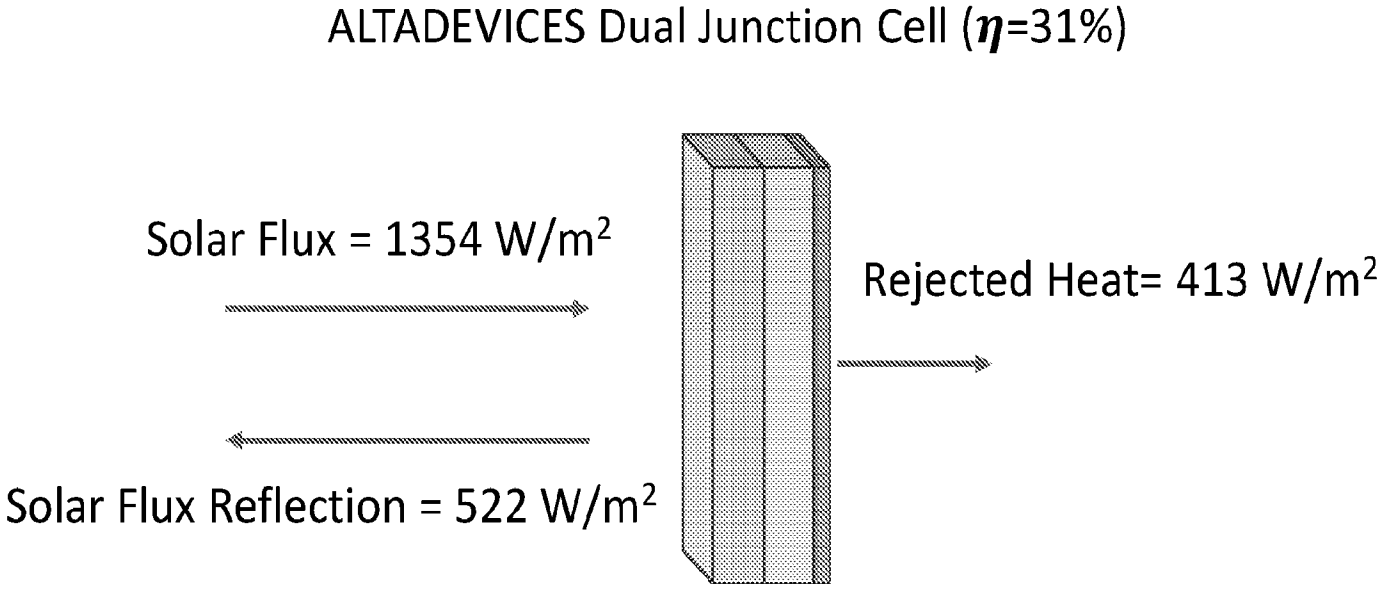

ALTADEVICES Dual Junction Cell (η=31%)
Solar Flux = 1354 W/m^2
Rejected Heat= 413 W/m^2
Solar Flux Reflection = 522 W/m^2
Flux Absorbed = 832 W/m^2
Flux Converted = 419 W/m^2

FIG. 25

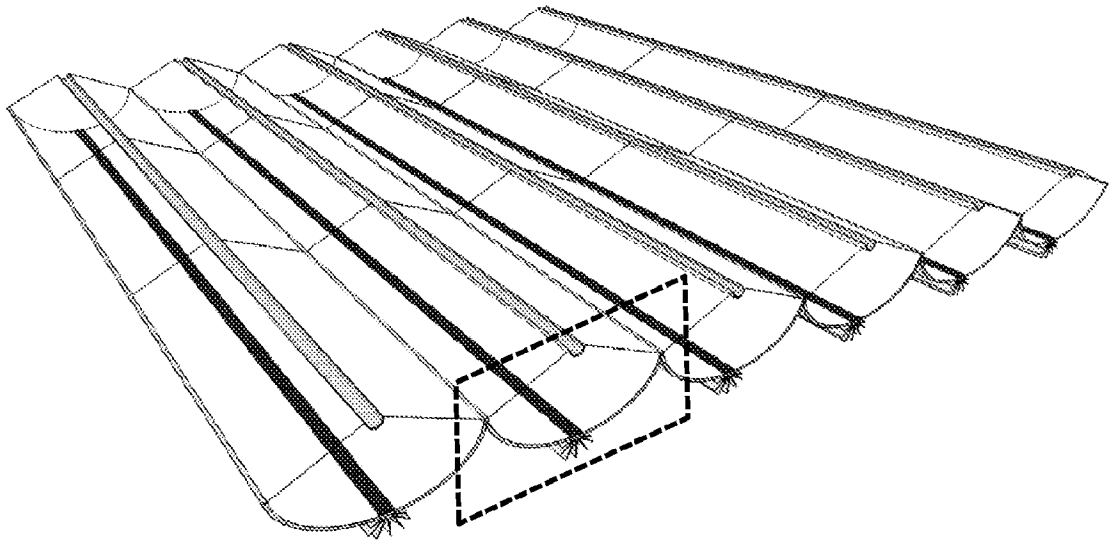


FIG. 26A

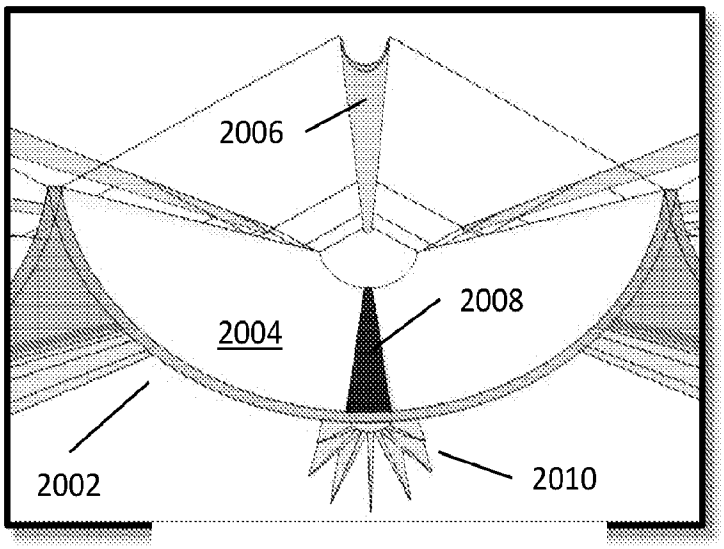


FIG. 26B

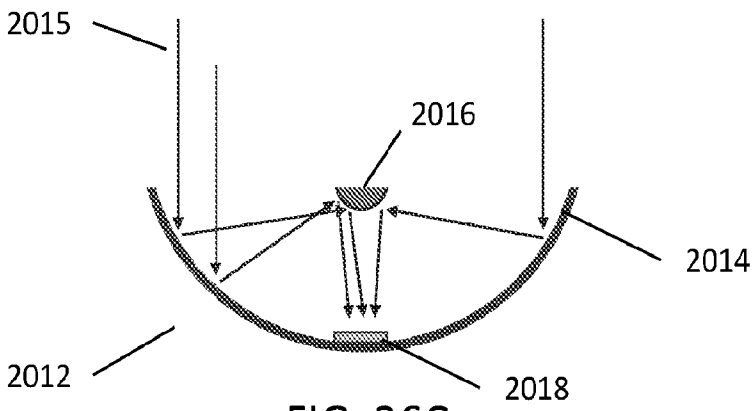


FIG. 26C

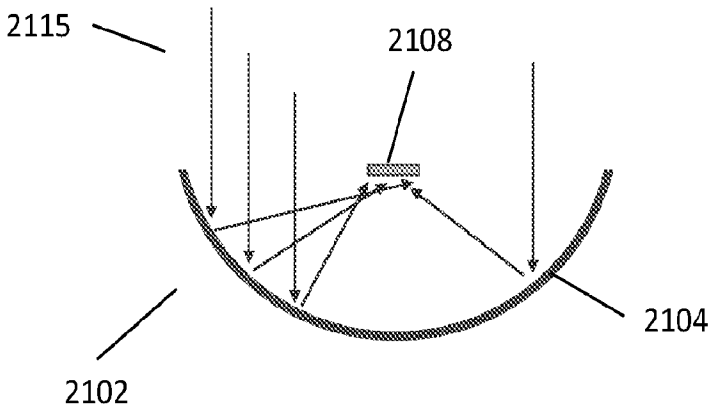


FIG. 27

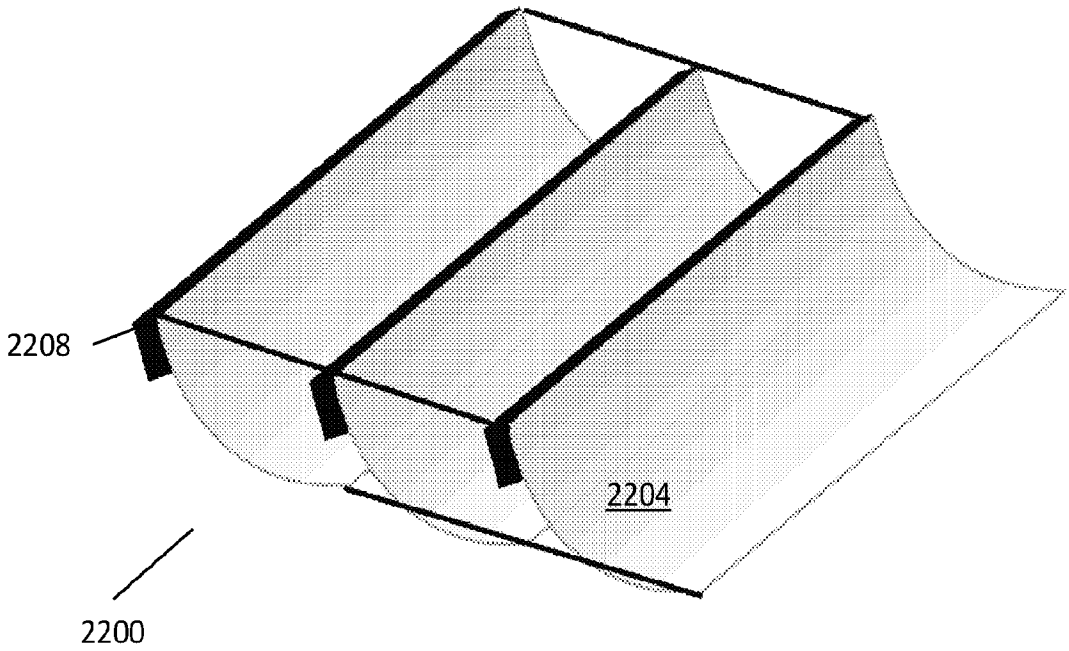


FIG. 28A

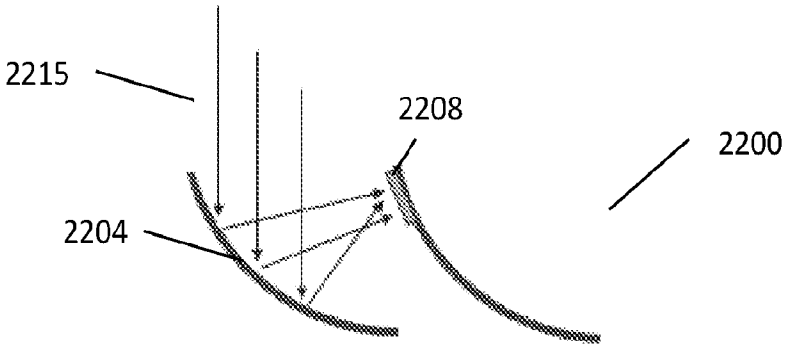


FIG. 28B

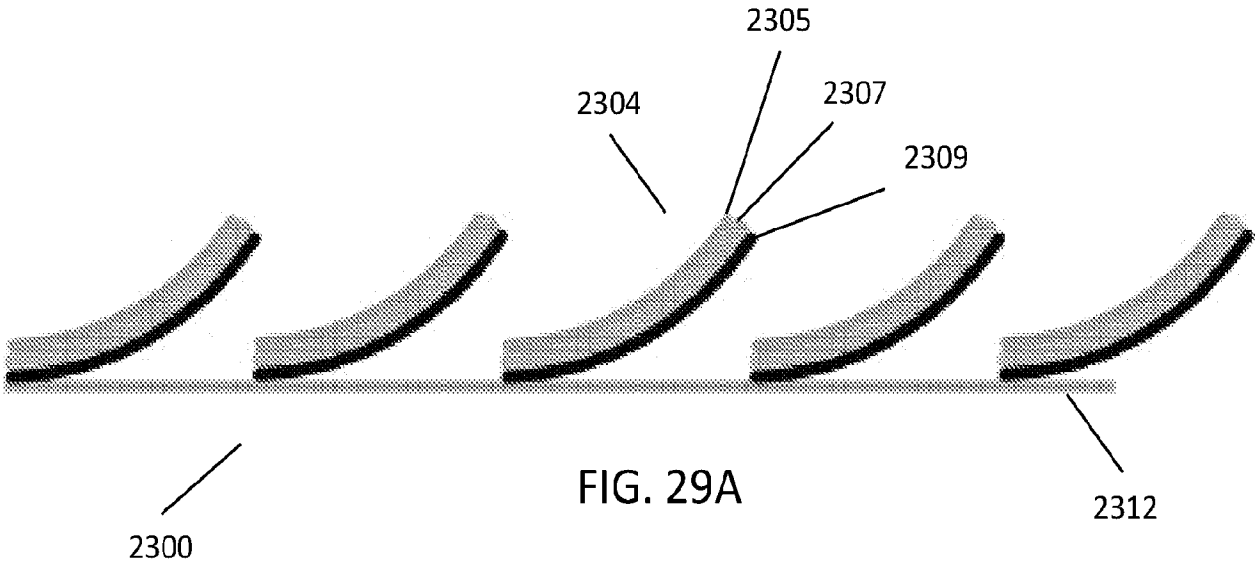


FIG. 29A

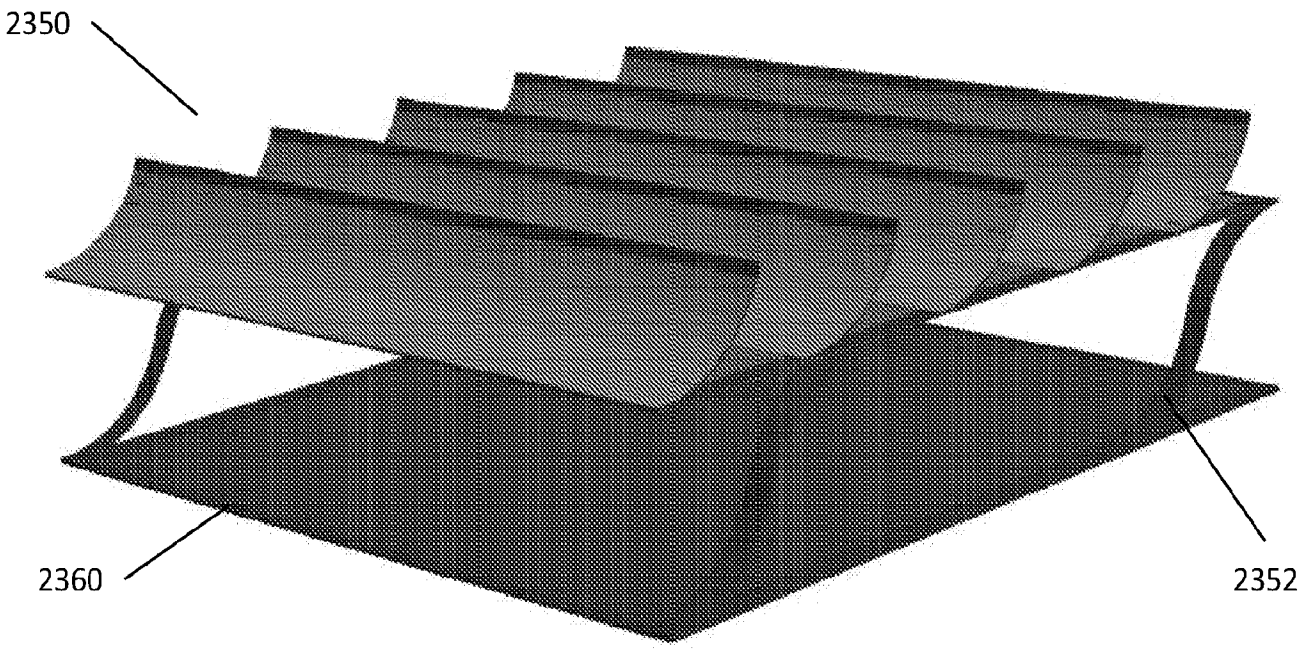


FIG. 29B

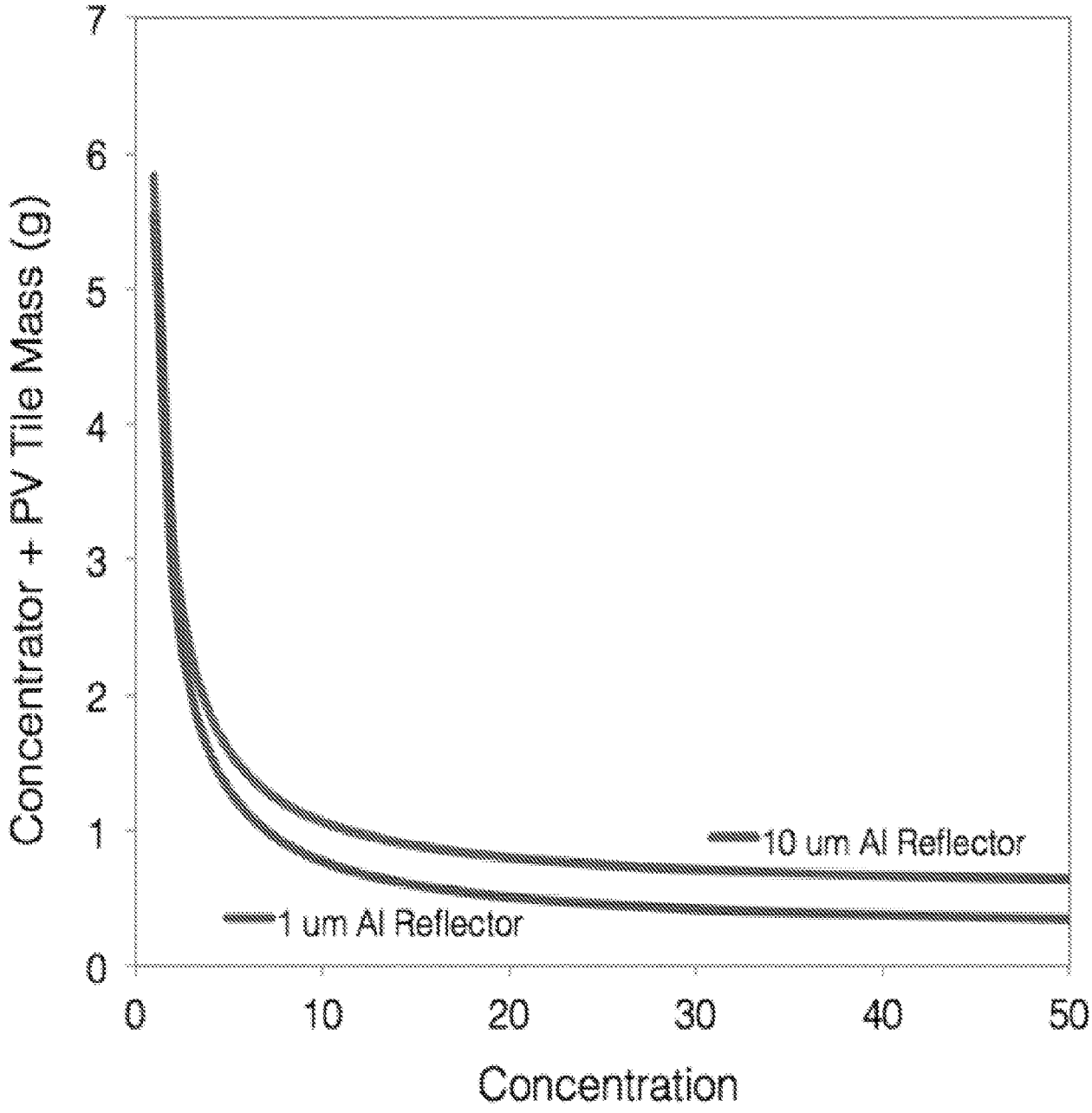

Concentrator + PV Tile Mass (g)
7
6
5
4
3
2
1
0
0
10
20
30
40
50
Concentration
10 um Al Reflector
1 um Al Reflector

FIG. 30

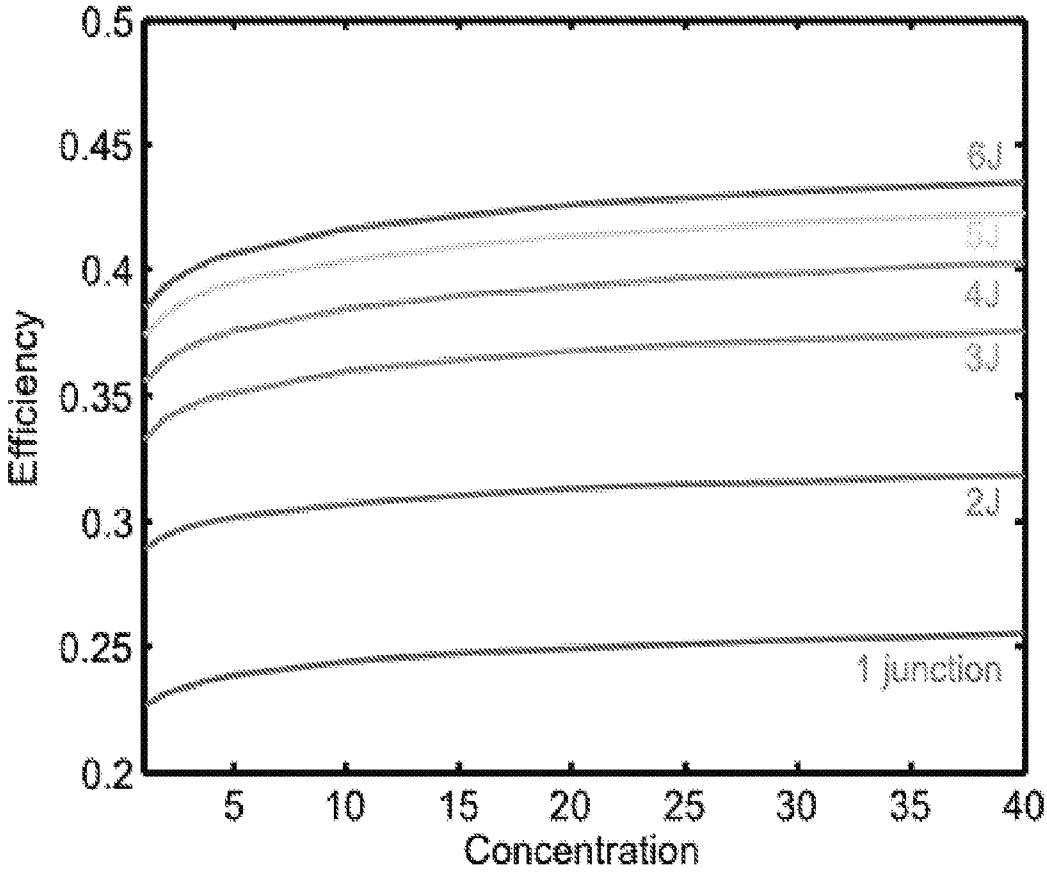

0.5
0.45
0.4
0.35
0.3
0.25
0.2
Efficiency
5
10
15
20
25
30
35
40
Concentration
6J
5J
4J
3J
2J
1 junction

FIG. 31

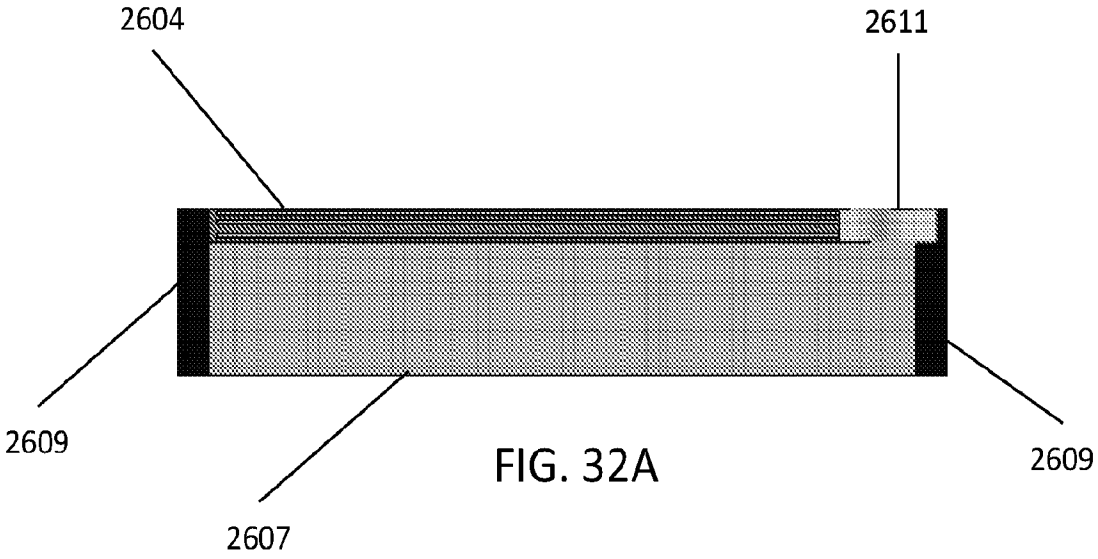


FIG. 32A

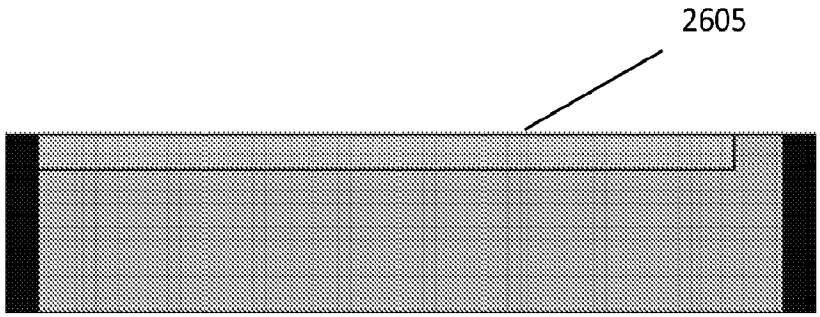


FIG. 32B

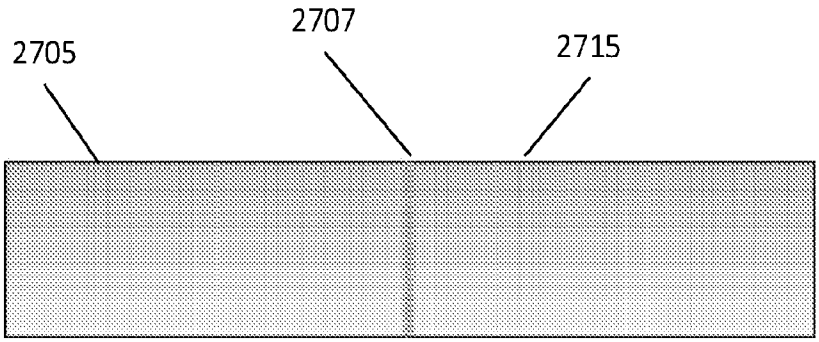


FIG. 33A

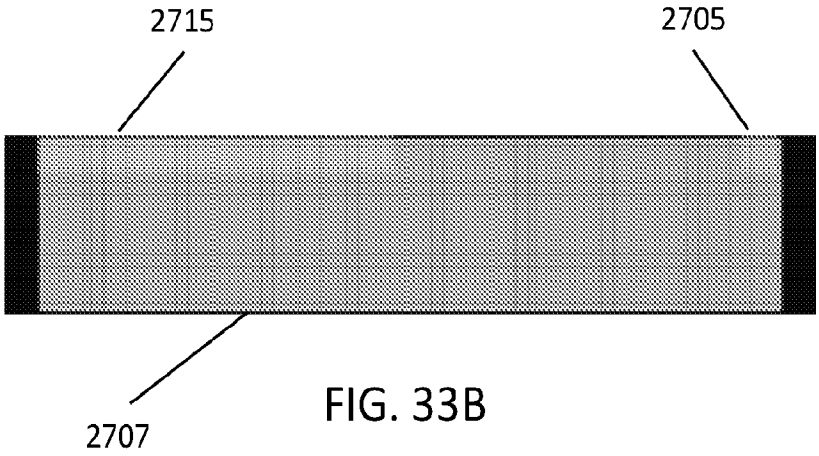


FIG. 33B

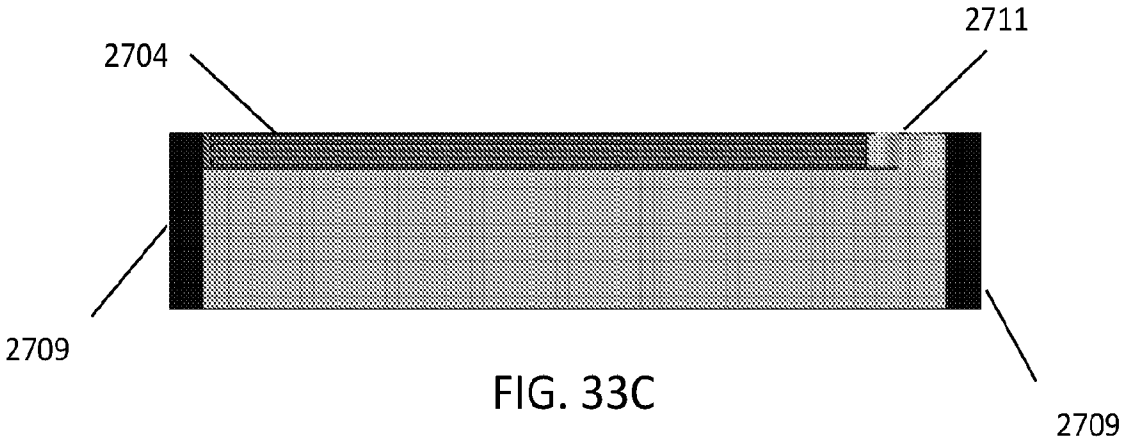


FIG. 33C

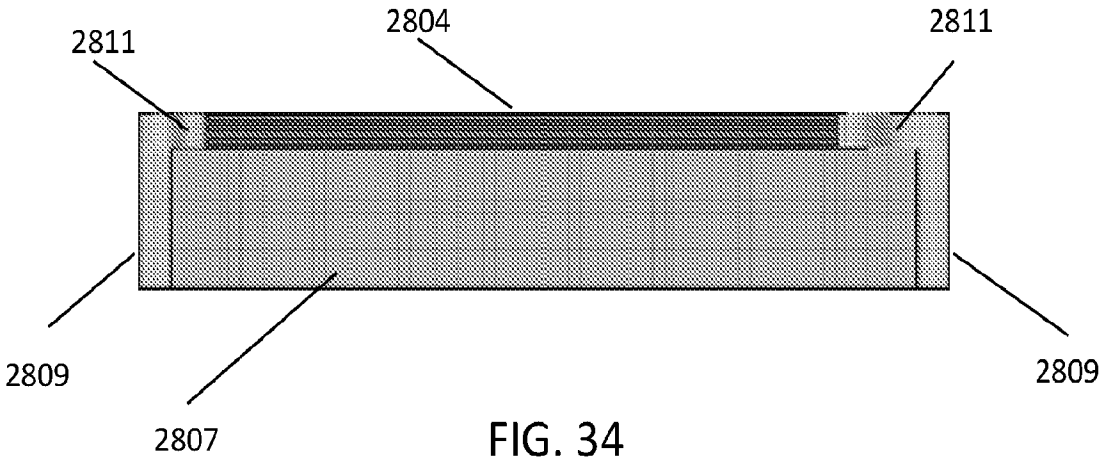


FIG. 34

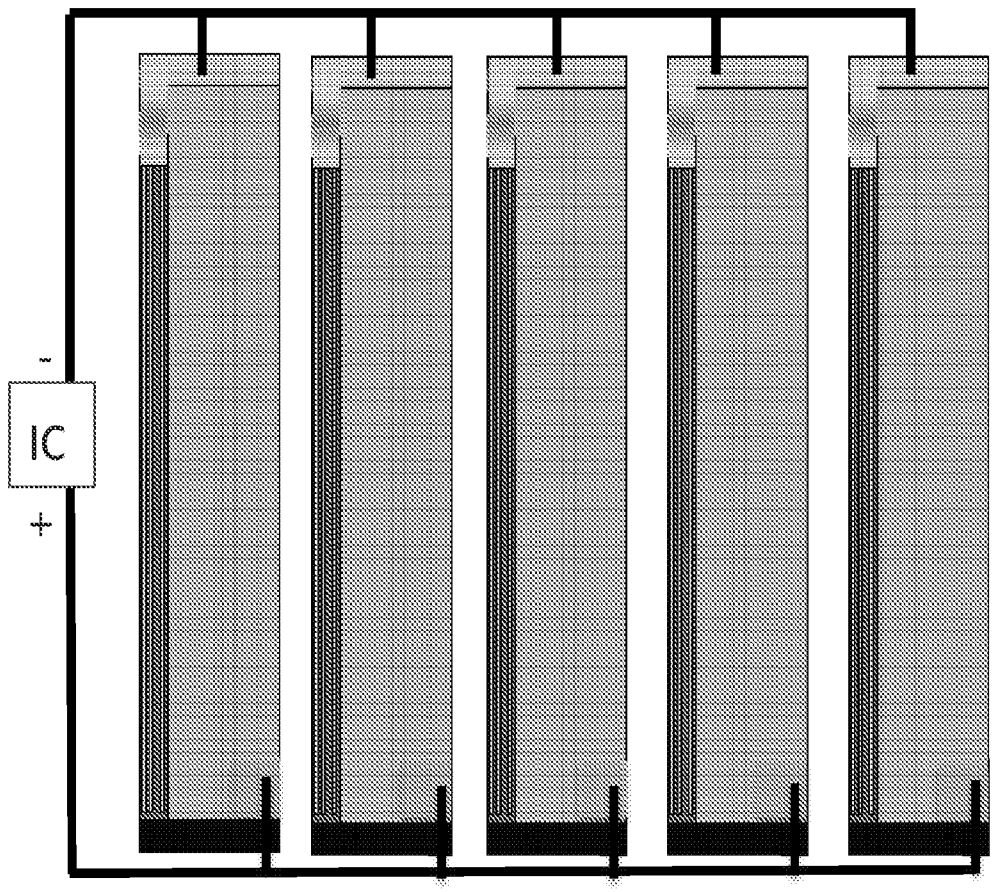


FIG. 35

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/043677

A. CLASSIFICATION OF SUBJECT MATTER

H02S 40/22(2014.01)i, H01L 31/054(2014.01)i, G01J 3/02(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)
H02S 40/22; B64G 1/26; G02B 27/14; B64G 1/44; H01Q 13/00; H01Q 3/02; H01L 31/052; H01L 31/054; G01J 3/02

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: photovoltaic, aluminum, mirror, sheet, transparent, microwave, spectrum, focus, light

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2008-0149162 A1 (GIULIANO MARTINELLI et al.) 26 June 2008 See abstract, claims 1-16 and figures 2-4.	1
A		2-20
Y	US 5512913 A (MICHAEL W. STANEY) 30 April 1996 See abstract, column 4, line 19-column 5, line 51 and figures 1-8.	1
A	US 2010-0269885 A1 (PABLO BENITEZ et al.) 28 October 2010 See abstract, paragraphs 61-100 and figures 1-12.	1-20
A	US 2011-0061718 A1 (DAVID K. FORK et al.) 17 March 2011 See abstract, claims 1-5 and figures 1-6.	1-20
A	JP 2003-191899 A (MASAKAZU INOUE) 09 July 2003 See abstract, claims 1-2 and figures 1-3.	1-20

☐ 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
21 October 2016 (21.10.2016)	**21 October 2016 (21.10.2016)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2016/043677

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		IT MI20050590 A1	09/10/2006
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		CN 101075646 A	21/11/2007
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JP 2003-191899 A	09/07/2003	None	