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(54) **SOLAR RECEIVER UTILIZING CARBON NANOTUBE INFUSED COATINGS**

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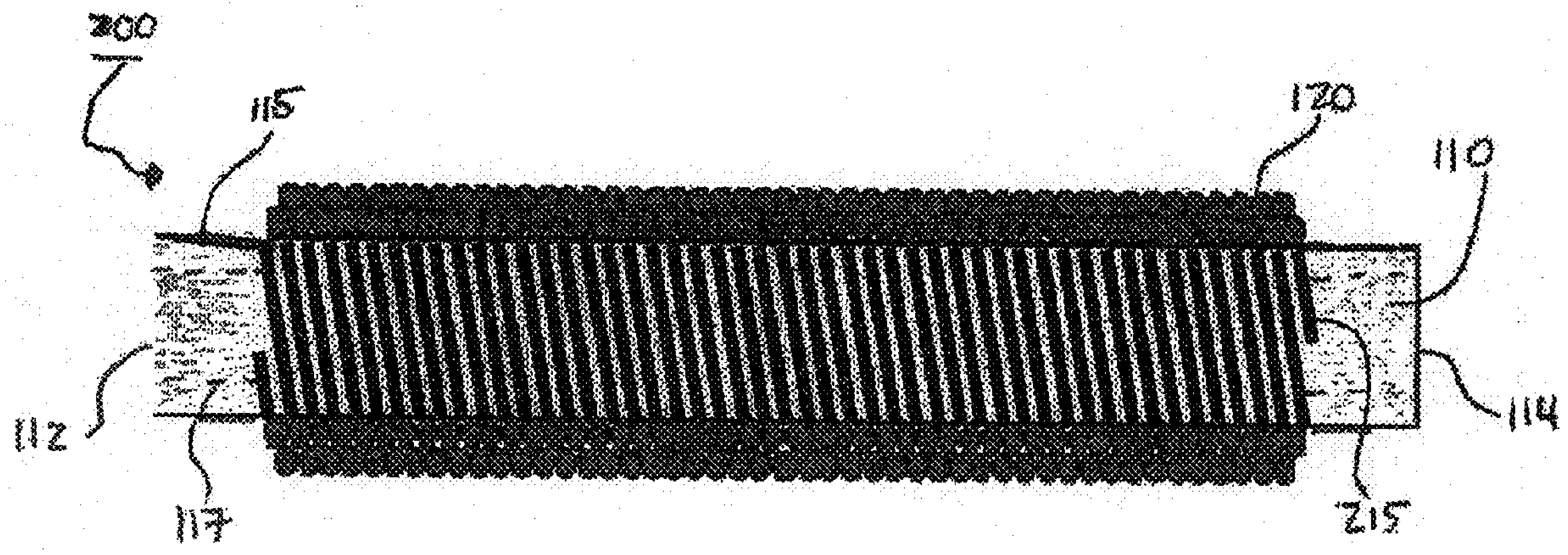
(57) **ABSTRACT**

A solar receiver includes a heat absorbing element having an outer surface and an inner surface opposite the outer surface and a first coating including a carbon nanotube-infused fiber material in surface engagement with and at least partially covering the outer surface of the heat absorbing element. Solar radiation incident onto the first coating is received, absorbed, and converted to heat energy, and the heat energy is transferred from the first coating to the heat absorbing element. A multilayer coating for a solar receiver device includes a first coating that includes a CNT-infused fiber material and an environmental coating disposed on the first coating.



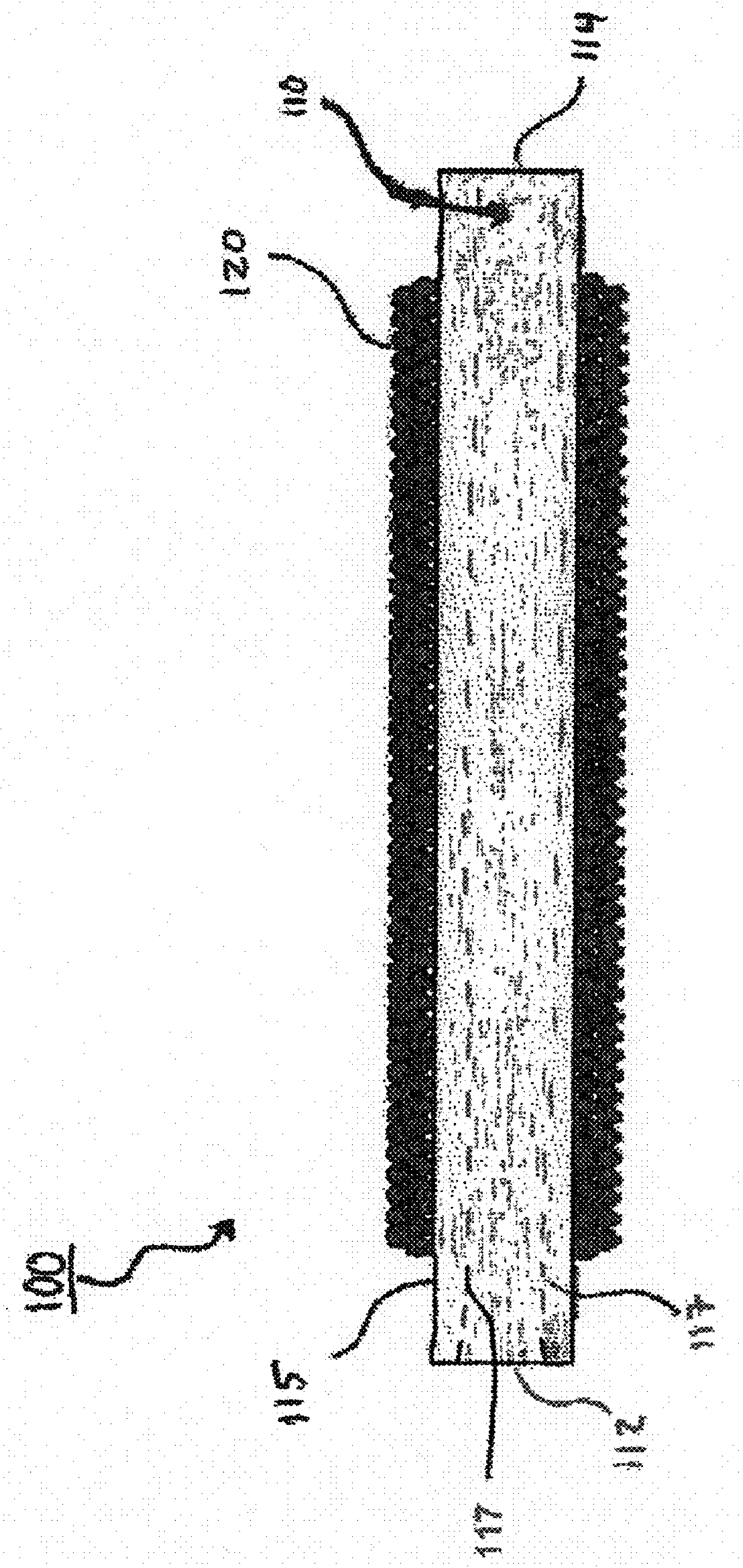


FIG. 1

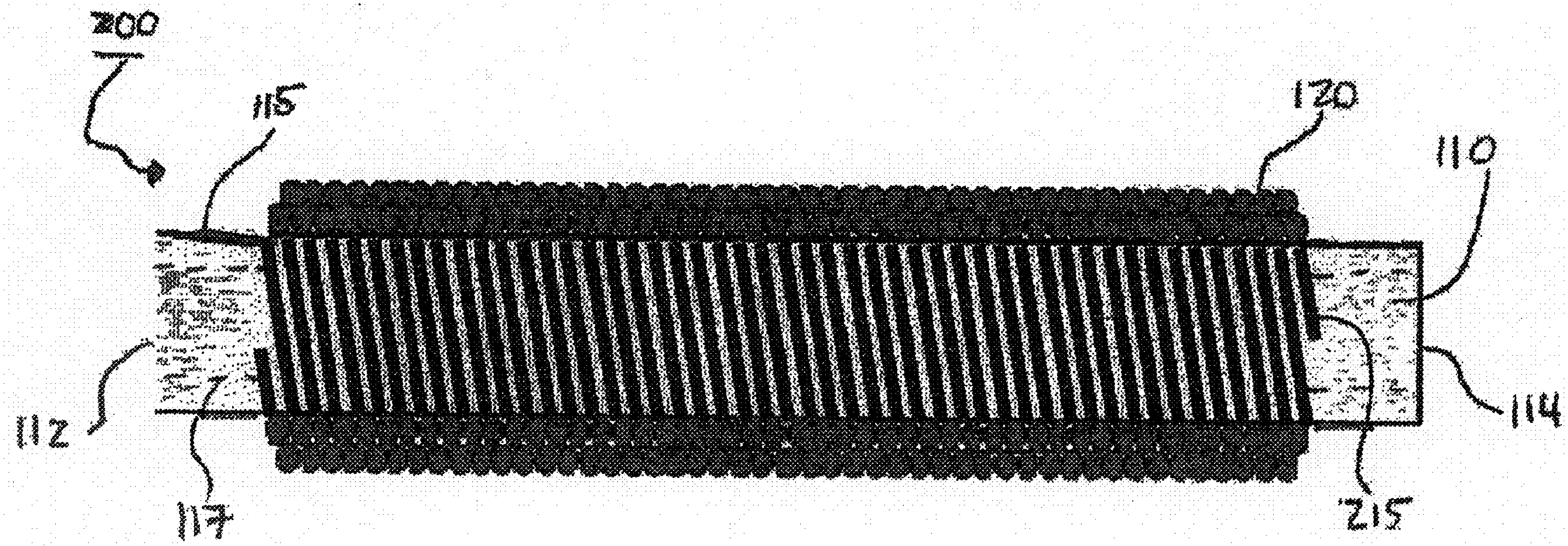


FIG 2

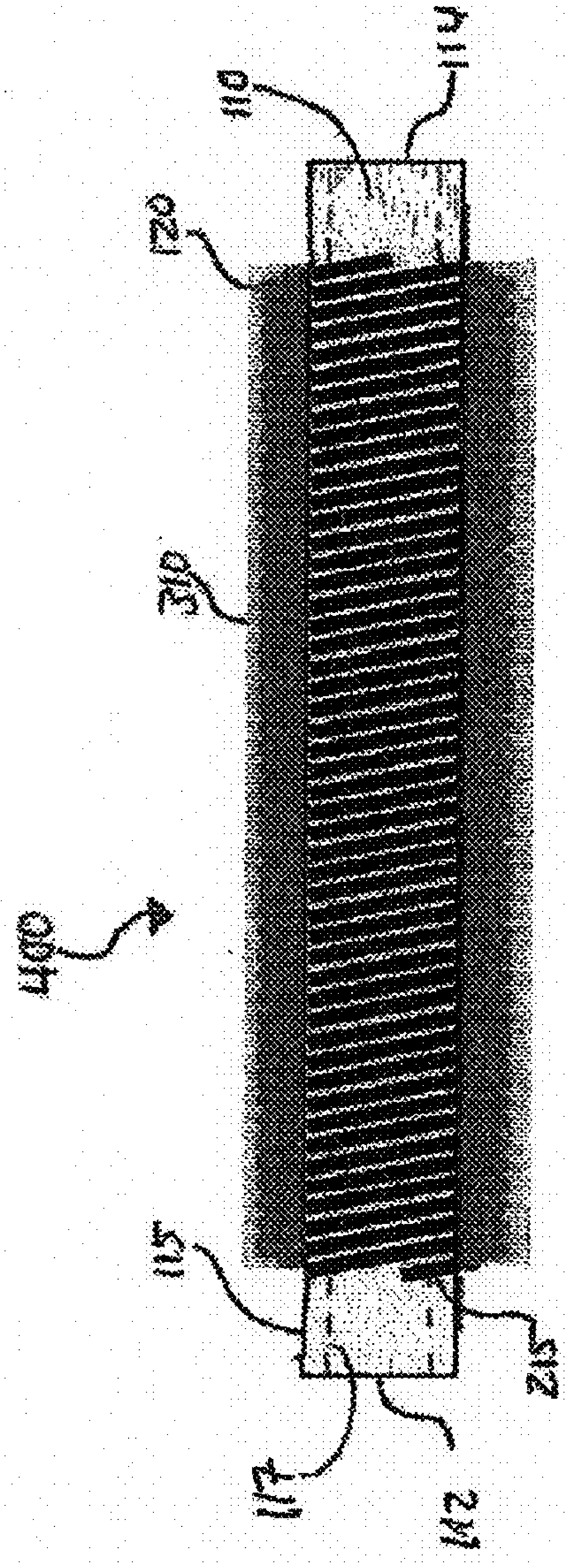

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Fig 4

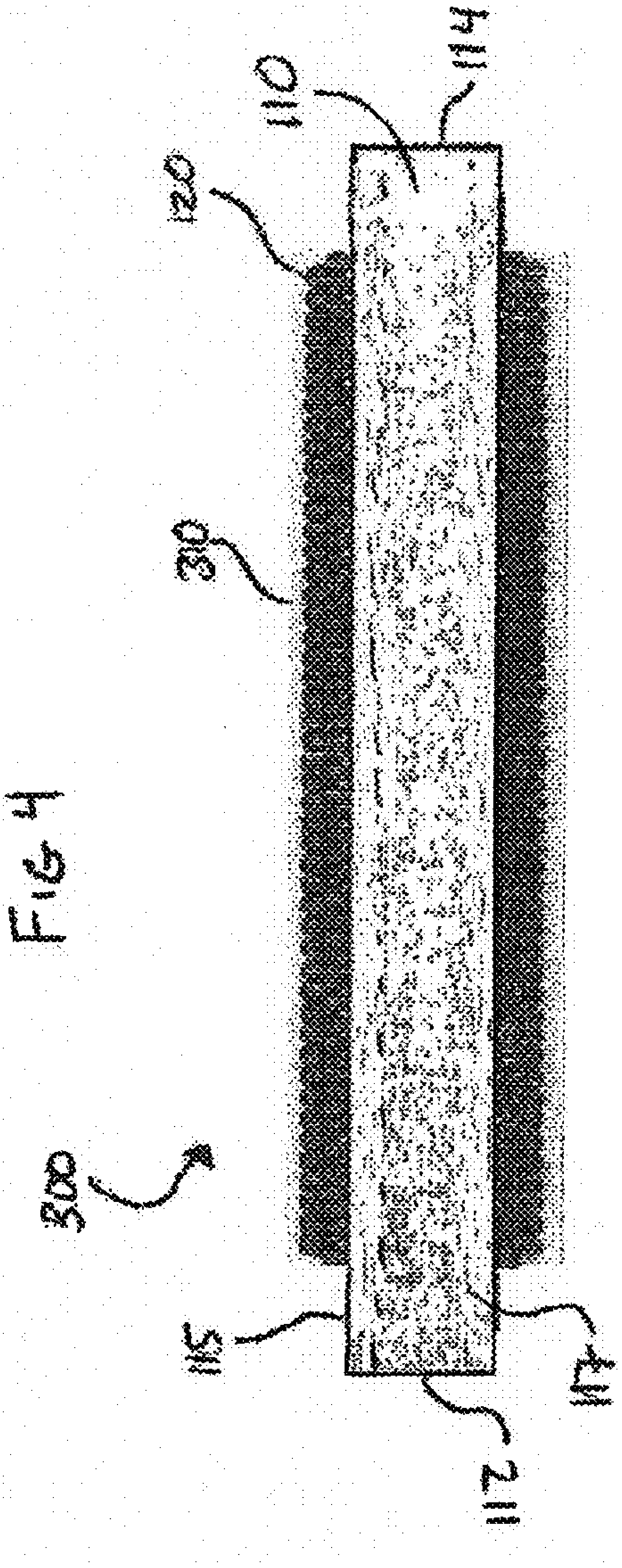
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Fig 3

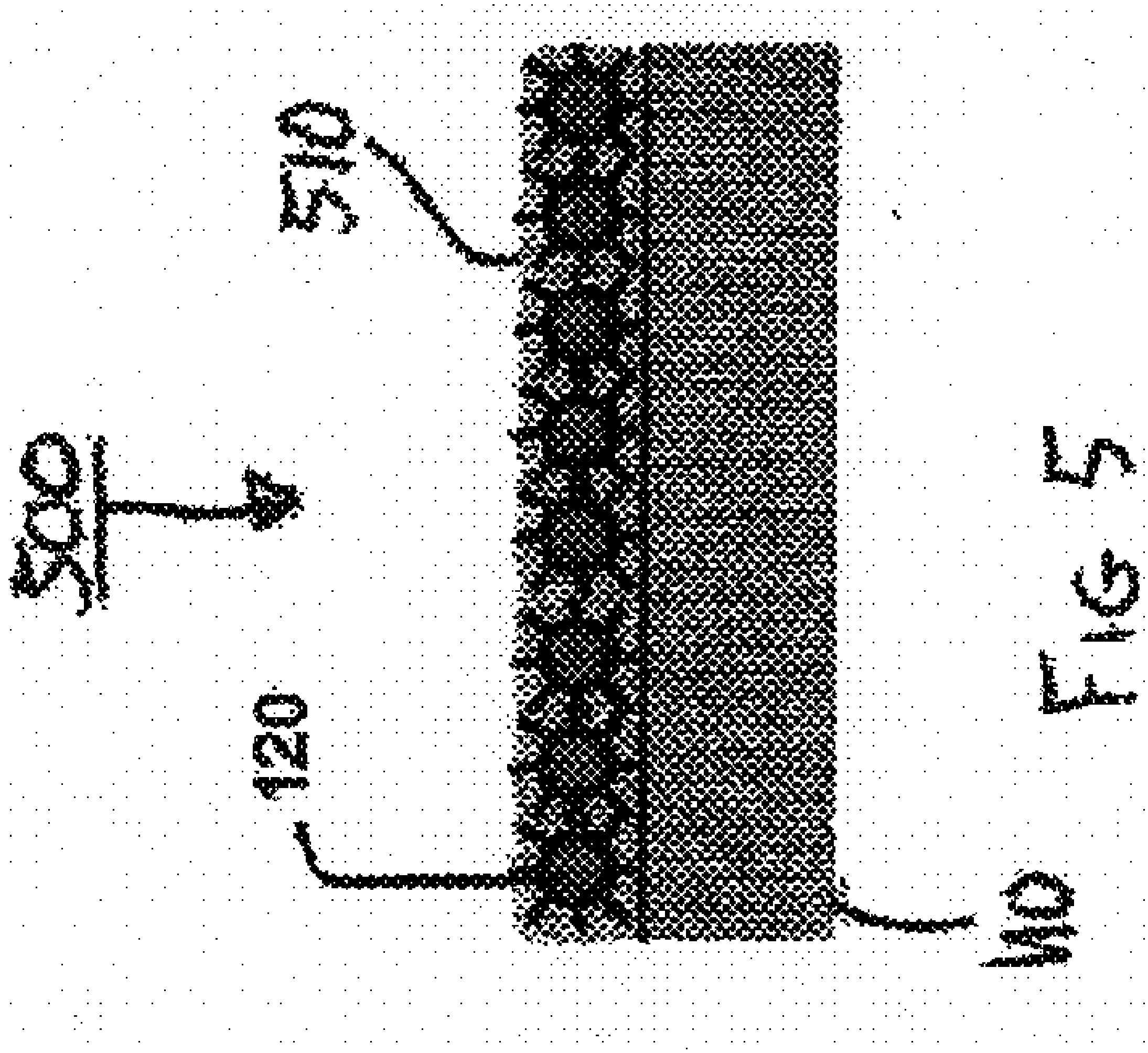


Fig 5

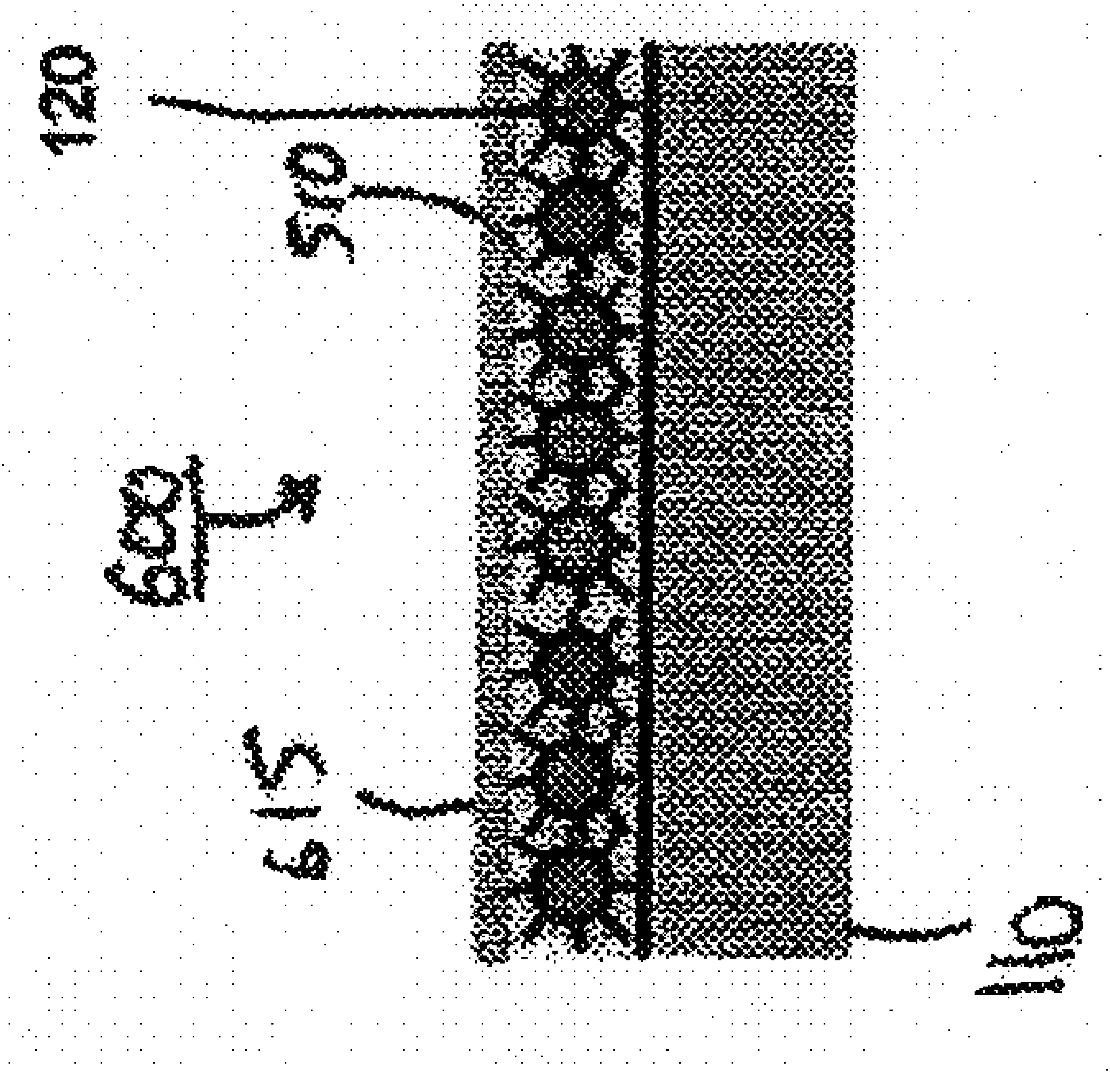


Fig 6

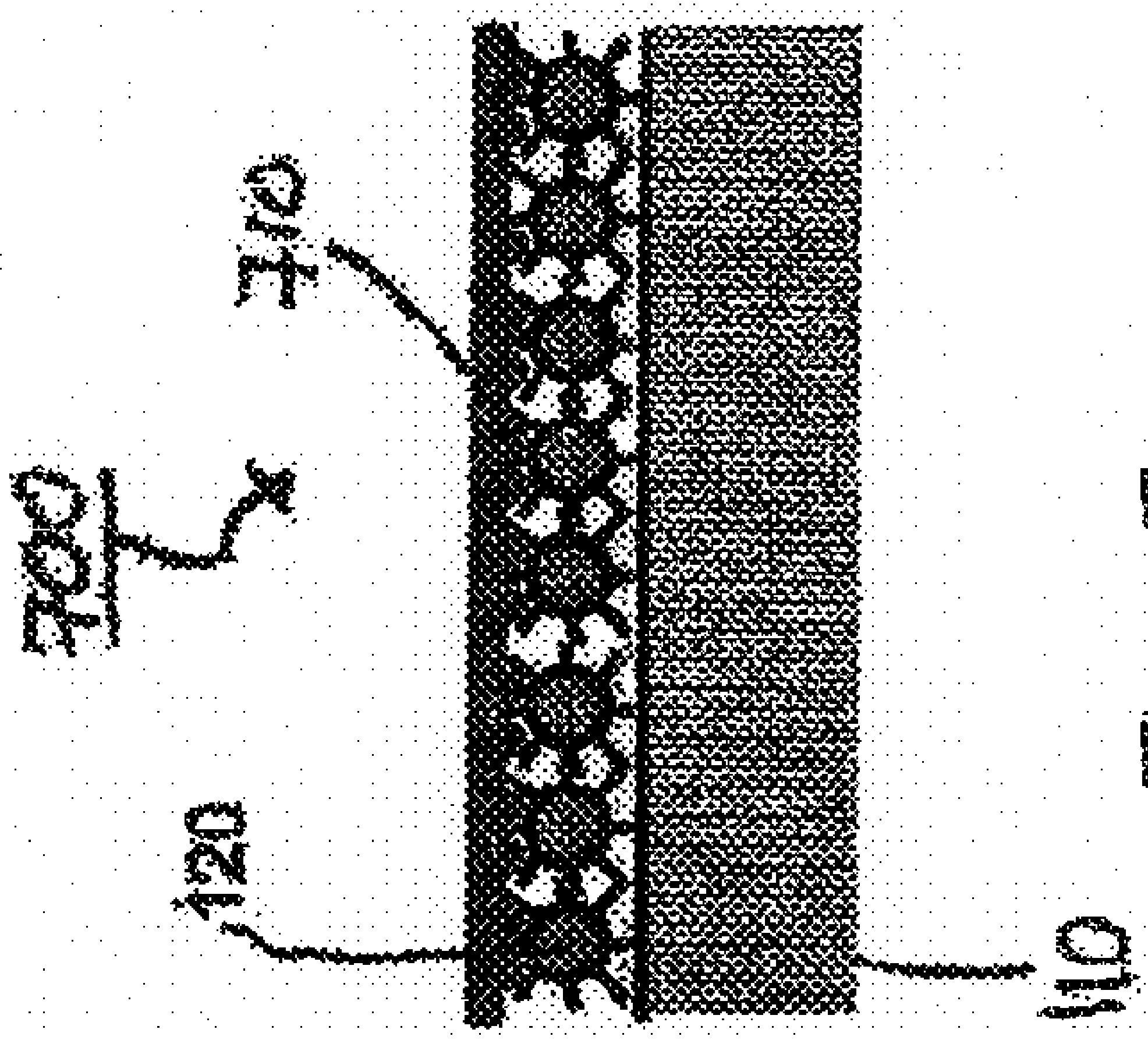


Fig 7

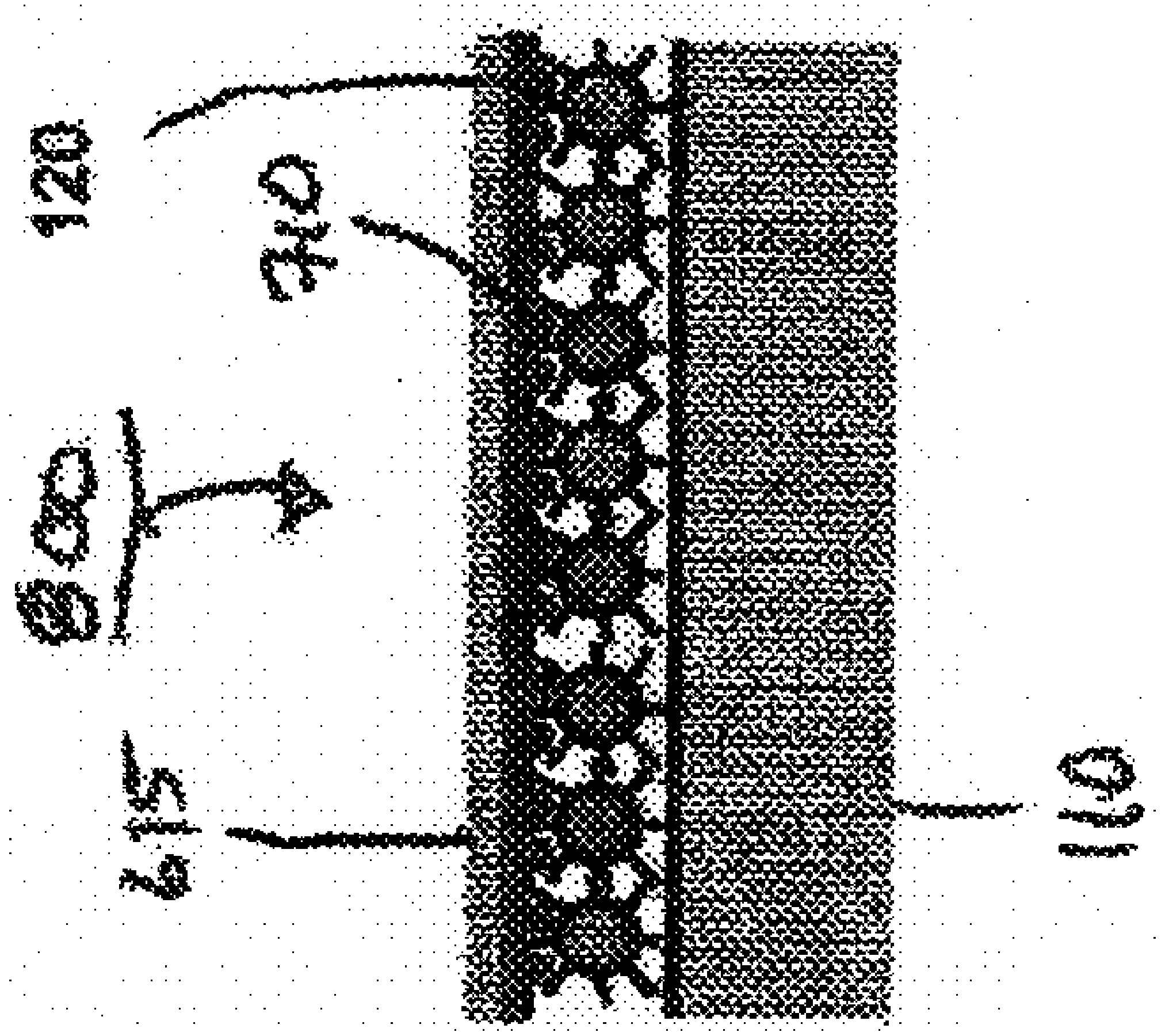


Fig 8

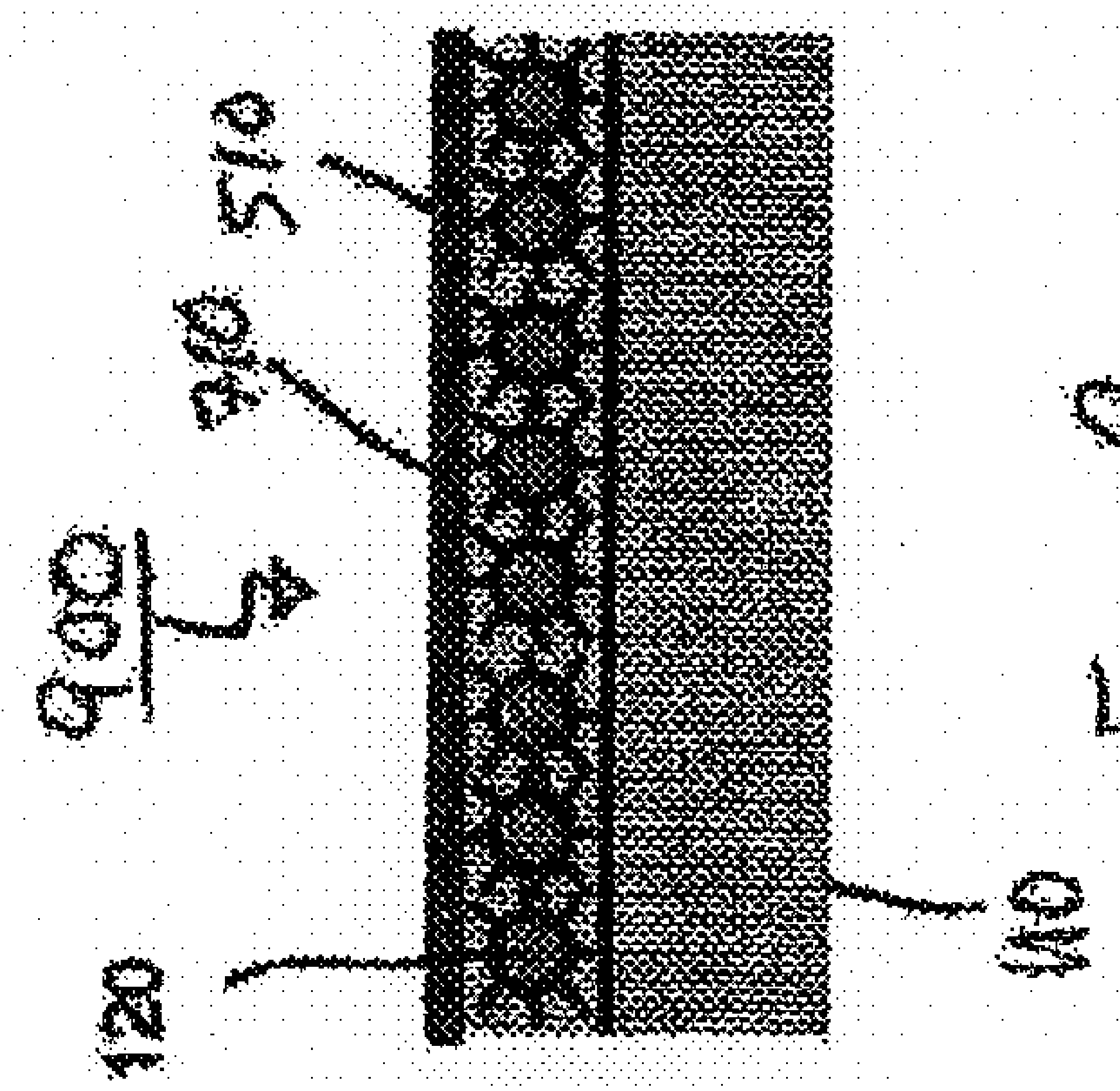


Fig 9

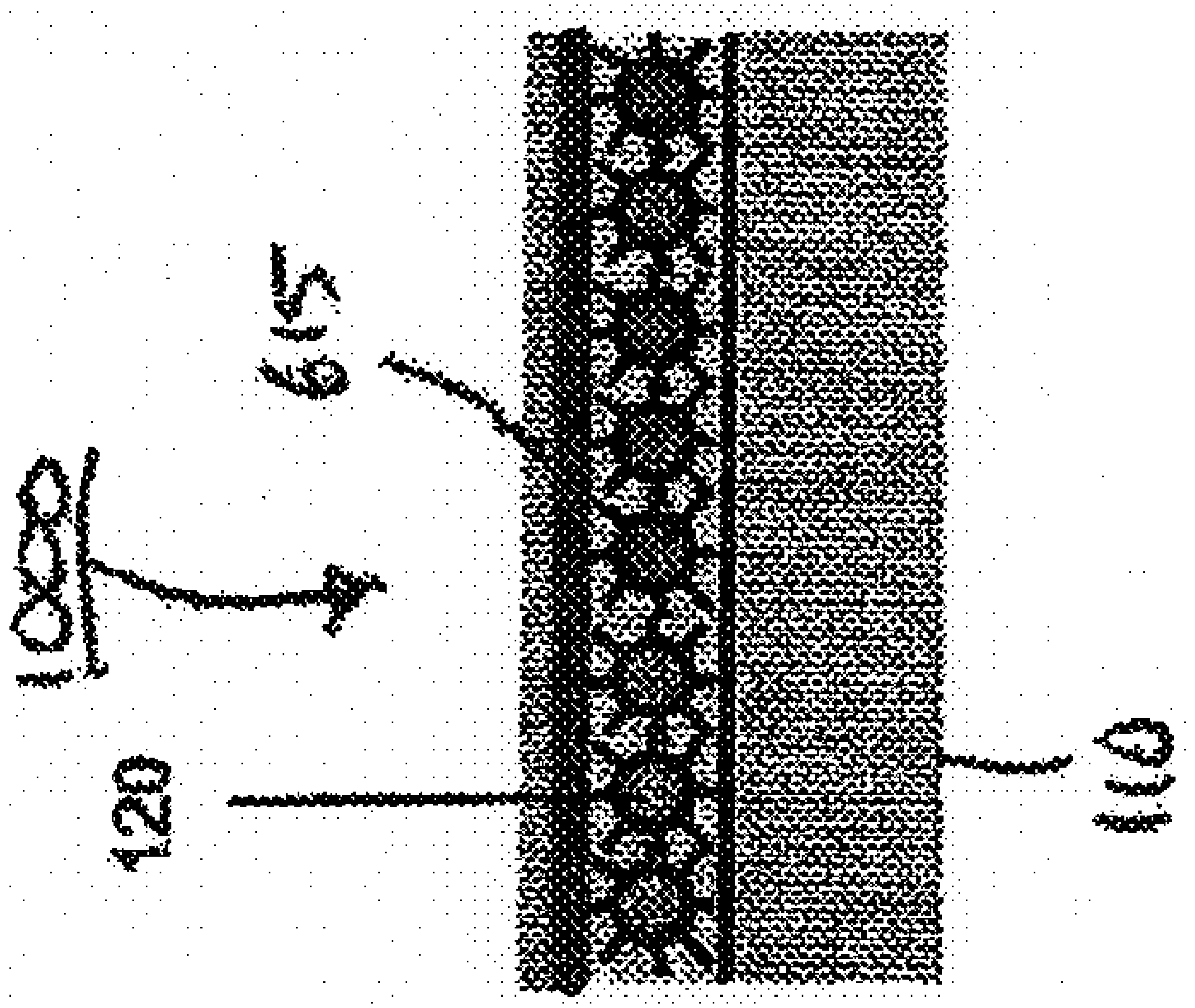


Fig 10

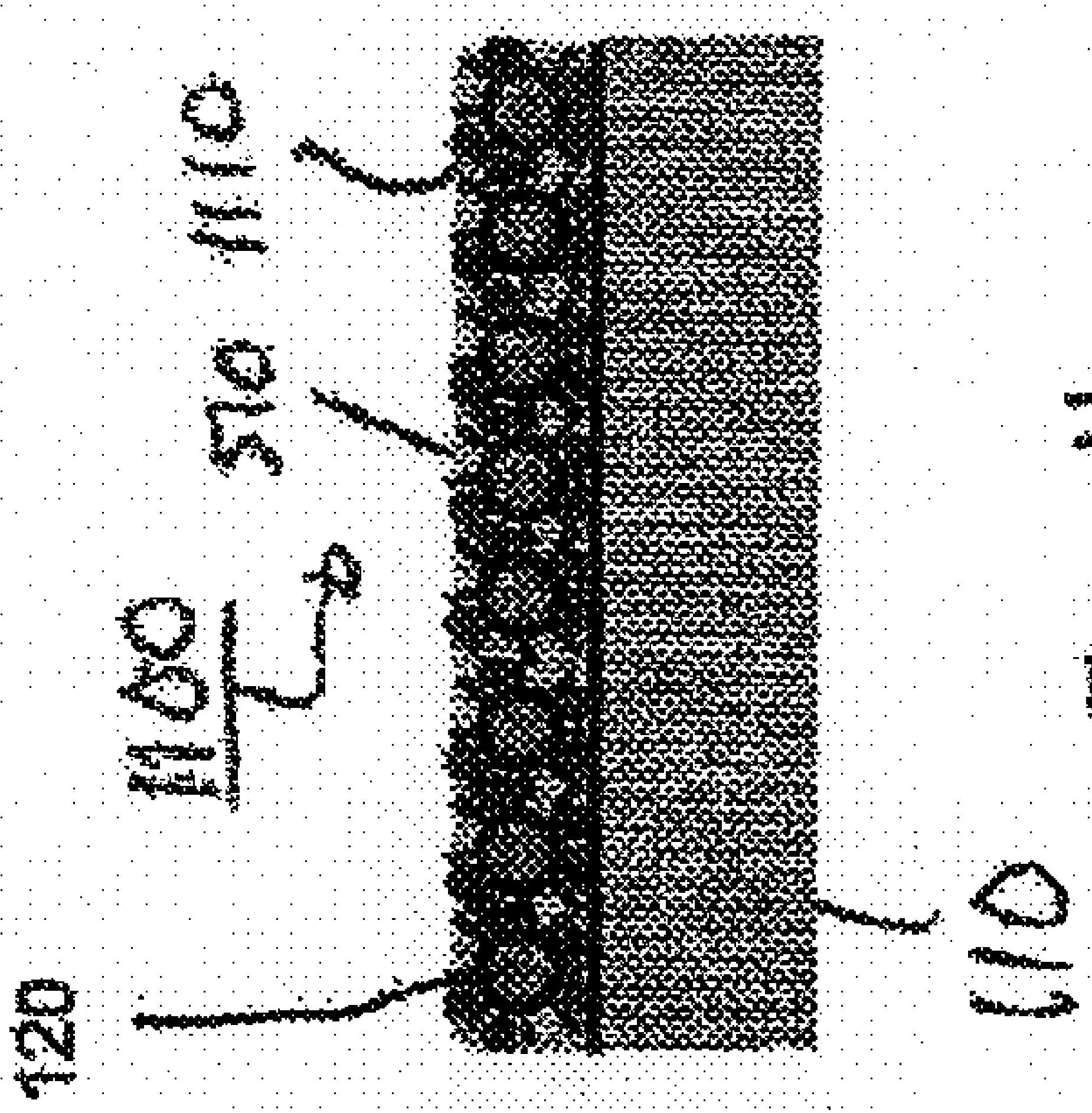


Fig 11

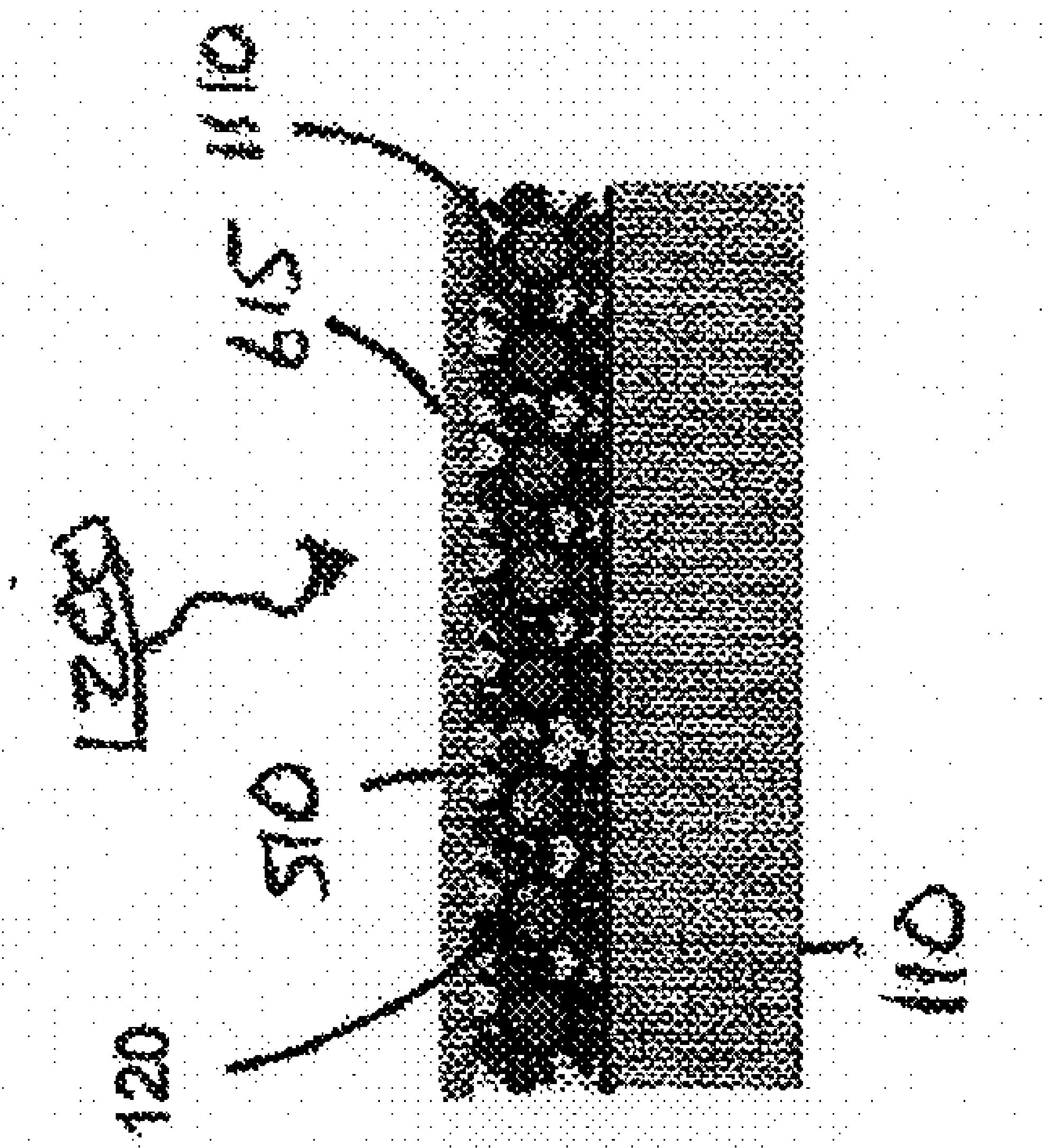
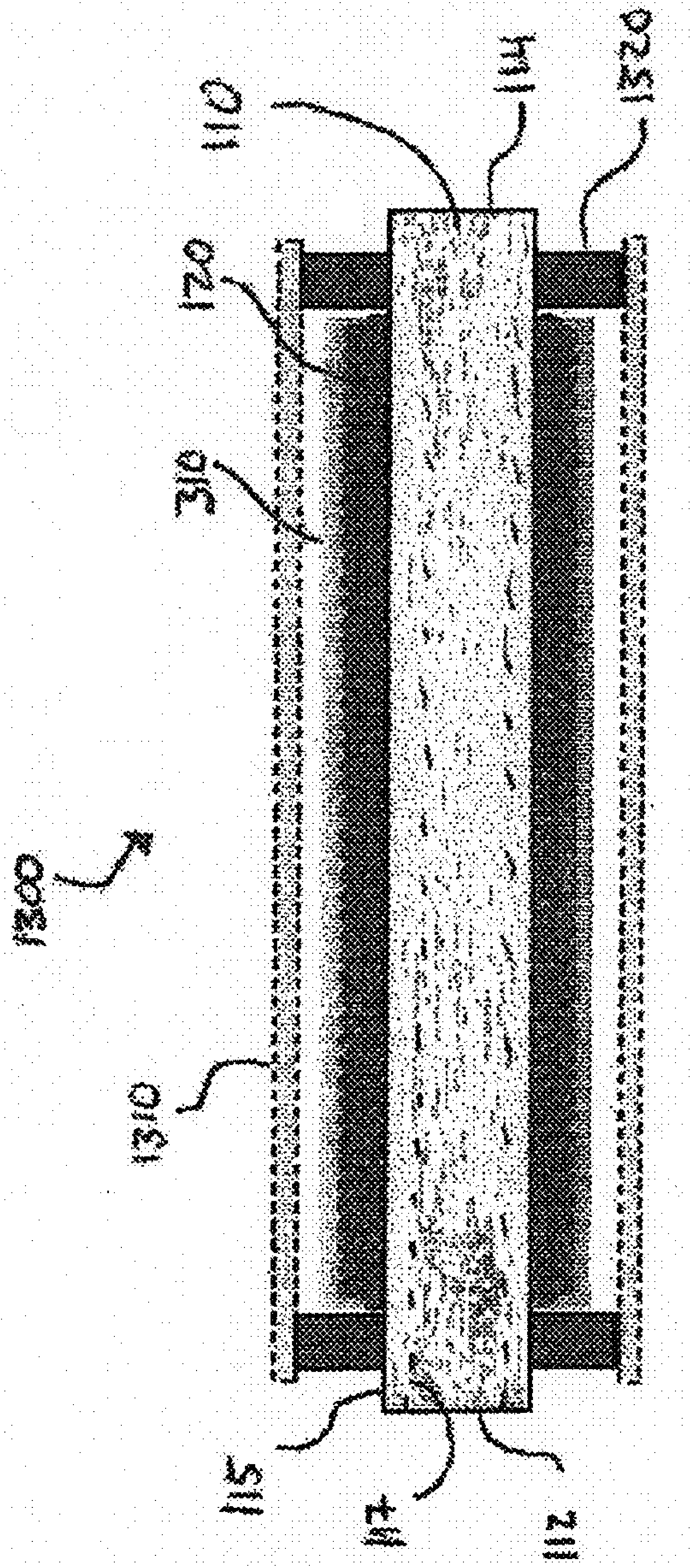


Fig 12


1300
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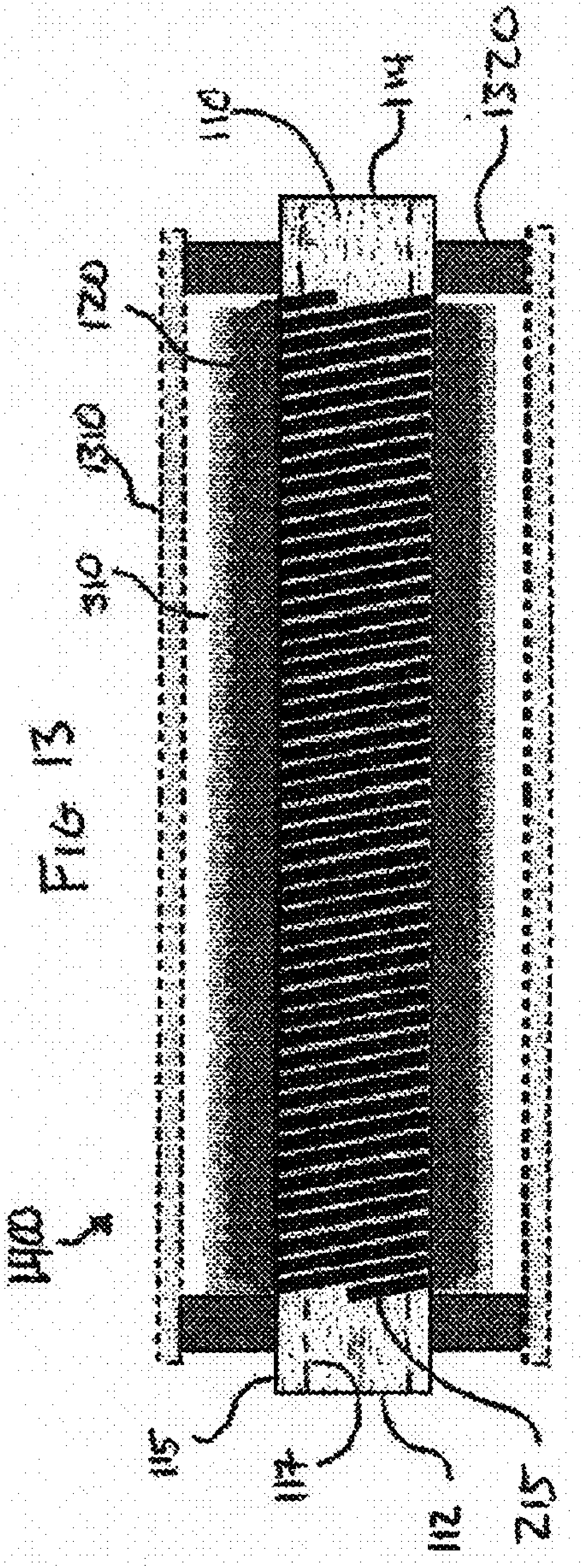
112

FIG 13


1400
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112
215

FIG 14

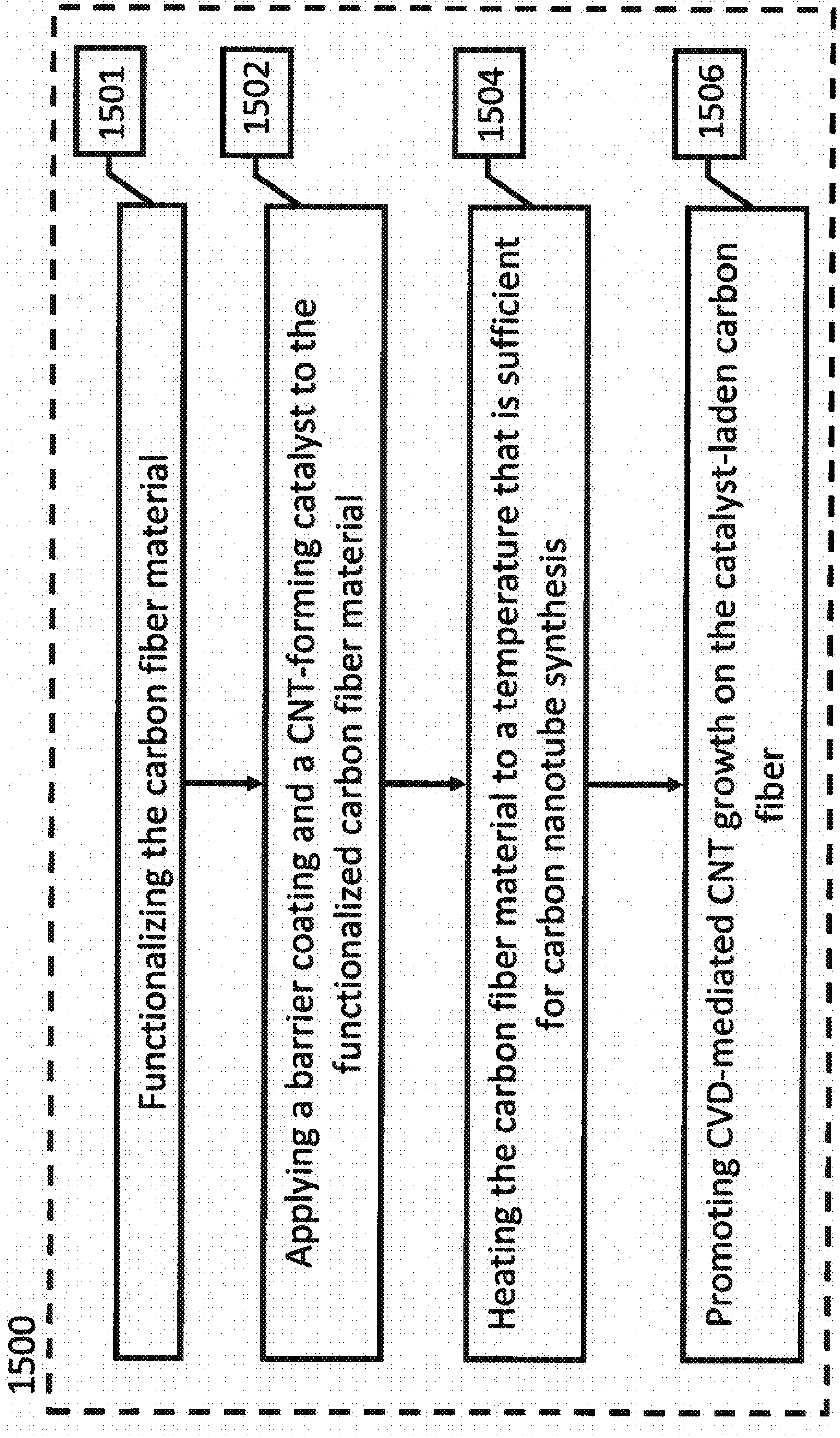
1500
1501
Functionalizing the carbon fiber material
1502
Applying a barrier coating and a CNT-forming catalyst to the functionalized carbon fiber material
1504
Heating the carbon fiber material to a temperature that is sufficient for carbon nanotube synthesis
1506
Promoting CVD-mediated CNT growth on the catalyst-laden carbon fiber

Figure 15

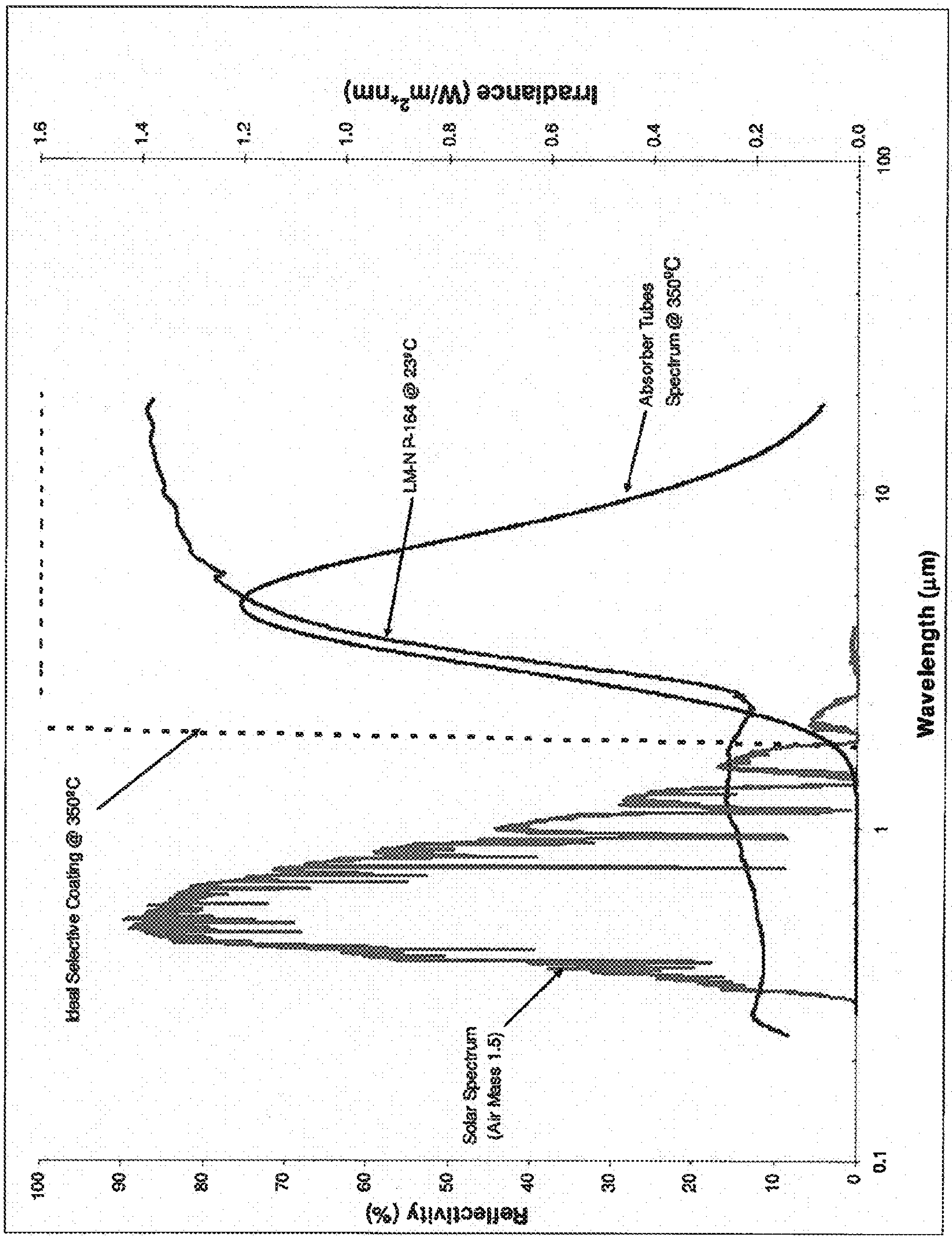
Irradiance (W/m^2*nm)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Reflectivity (%)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
Wavelength (µm)
Ideal Selective Coating @ 350°C
Solar Spectrum
(Air Mass 1.5)
LM-N R-164 @ 23°C
Absorber Tubes
Spectrum @ 350°C

Figure 16

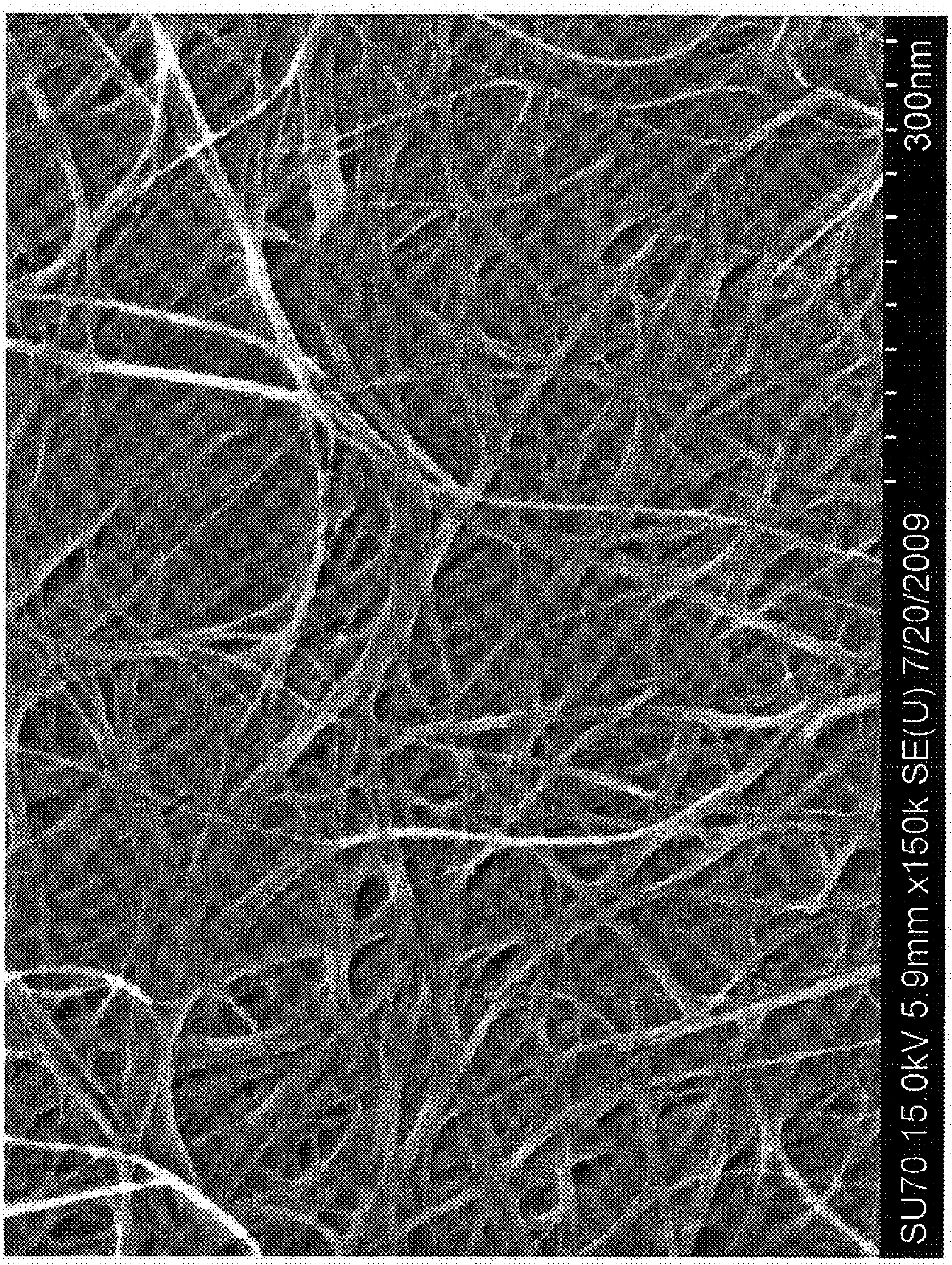

Figure 17

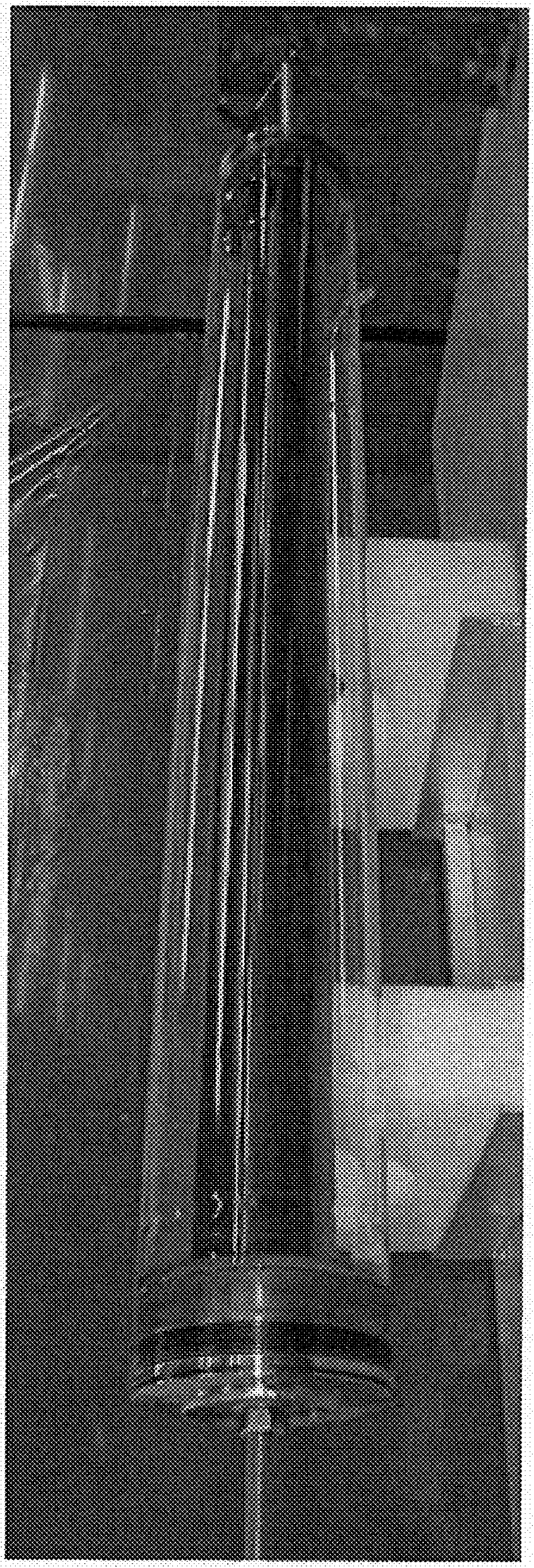

Figure 18

SOLAR RECEIVER UTILIZING CARBON NANOTUBE INFUSED COATINGS

STATEMENT OF RELATED APPLICATIONS

[0001] This application claims priority under 35 U.S.C. 119 (e) to U.S. Provisional Application 61/167,386 filed Apr. 7, 2009.

FIELD OF INVENTION

[0002] The present invention relates in general to a solar receiver apparatus for receiving, absorbing, containing, and converting received electromagnetic radiation into heat energy.

BACKGROUND

[0003] Solar thermal collectors have been developed to harness the energy from solar radiation for various industrial processes, power generation and water heating applications. Solar radiation incident onto the earth's surface has an estimated power density of about 1 kW/m^2 and wavelengths ranging from about 200 nanometers (nm) for ultraviolet (UV) radiation to about 2500 nm for infrared (IR) radiation. Solar thermal collectors generally include a reflector to focus the solar radiation onto a thermal receiver. The thermal receiver converts the photonic energy of the solar radiation into thermal energy of a heat transfer fluid. Thermal receivers generally include a thermal absorber which is a good absorber of short-wave solar radiation, for example in the UV and visible range. However, at least some thermal absorbers are also good long-wave heat radiators in the infrared range, emitting heat via IR radiation, when sufficiently excited by the absorption of short-wave solar radiation. Although a high percentage of incident solar radiation may be initially absorbed, thermal absorbers can emit a high percentage as radiated heat, thereby lowering the effective collection of the solar energy.

[0004] Several types of solar collectors have been developed, including but not limited to flat plate solar collectors and absorber tubes contained in evacuated glass tube housing. Absorber surfaces can include a bare metal or a metal coated with a selective absorber coating for absorbing radiation within the solar radiation spectrum (i.e., about 200 nm to 2500 nm). Such solar selective absorber coatings (having absorptivity, for example, in the range of 0.92 to 0.96 and emissivity, for example, in the range of 0.07 to 0.11) absorb practically all incident radiation but do not generally emit heat at infra-red wavelengths. Examples of such solar selective absorber coatings include very thin black metallic oxide coating (e.g., on the order of about 0.5 to 1.0 microns) on a highly reflective metal base, and galvanically applied selective coatings such as black chrome, black nickel, and aluminum oxide with nickel. Absorber tubes coated with solar selective coatings are generally encased in glass tubes or evacuated glass tubes to minimize the loss of heat to the ambient air via convection. However, the evacuated glass tubes generally used in conjunction with some of these coatings are costly to fabricate and prone to damage when deployed. Additional components such as shrouds are often employed to protect the vacuum seals from direct thermal radiation, which results in losses in efficiency of about 2% Alternative solar receivers having good absorbance and low emissivity characteristics are, therefore, desirable. The present invention satisfies this need and provides related advantages as well.

SUMMARY OF THE INVENTION

[0005] In some aspects, embodiments disclosed herein relate to a solar receiver that includes a heat absorbing element having an outer surface and an inner surface opposite the outer surface; and a first coating including a carbon nanotube-infused fiber material in surface engagement with and at least partially covering the outer surface of the heat absorbing element. Solar radiation incident onto the first coating is received, absorbed, and converted to heat energy, and the heat energy is transferred from the first coating to the heat absorbing element.

[0006] In some aspects, embodiments disclosed herein relate to a multilayer coating for a solar receiver device that includes a first coating having a CNT-infused fiber material and an environmental coating disposed on the first coating.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** is a profile view of an exemplary solar receiver having a CNT-infused coating on the outer surface of a heat absorbing element.

[0008] FIG. **2** is a profile of a solar receiver as shown in FIG. **1**, further including grooves on the outer surface of the heat absorber element.

[0009] FIG. **3** is a profile view of a solar receiver as shown in FIG. **1**, further including an environmental coating over the CNT-infused coating.

[0010] FIG. **4** is a profile view of a solar receiver as shown in FIG. **3**, further including grooves on the outer surface of the heat absorber element, according to a fourth embodiment of the invention;

[0011] FIG. **5** is a cross-sectional view of a ceramic low emissivity, environmental coating integrated into a CNT-infused coating and applied to an outer surface of a heat absorber element of a solar receiver, according to an embodiment of the invention;

[0012] FIG. **6** is a cross-sectional view of the ceramic low emissivity, environmental integrated coating of FIG. **5**, further including an anti-reflective coating, according to an embodiment of the invention;

[0013] FIG. **7** is a cross-sectional view of a metallic low emissivity, environmental coating applied over the CNT-infused coating, according to an embodiment of the invention;

[0014] FIG. **8** is a cross-sectional view of an anti-reflective coating applied over the metallic low emissivity, environmental integrated coating as shown in FIG. **7**, according to an embodiment of the invention;

[0015] FIG. **9** is a cross-sectional view of a layered cermet low emissivity, environmental integrated coating applied over the integrated coating as shown in FIG. **5**, according to an embodiment of the invention;

[0016] FIG. **10** is a cross-sectional view of the layered cermet low emissivity, environmental integrated coating as shown in FIG. **9**, further including an anti-reflective coating, according to an embodiment of the invention;

[0017] FIG. **11** is a cross-sectional view of an integrated cermet low emissivity, environmental CNT-infused coating applied on an outer surface of a heat absorber element of a solar receiver, according to an embodiment of the invention;

[0018] FIG. **12** is a cross-sectional view of the integrated cermet low emissivity, environmental CNT-infused coating as shown in FIG. **11**, further including an anti¬reflective coating, according to an embodiment of the invention;

[0019] FIG. **13** is a cross-sectional view of a solar receiver with an annulus, according to an embodiment of the invention;

[0020] FIG. **14** is a cross-sectional view of a solar receiver as shown in FIG. **13**, further including grooves as described in the second embodiment shown in FIG. **2**, according to an embodiment of the invention.

[0021] FIG. **15** shows a process for producing CNT-infused carbon fiber material in accordance with the illustrative embodiment of the present invention.

[0022] FIG. **16** shows reflectivity data for a coating that includes a CNT-infused fiber material.

[0023] FIG. **17** shows a scanning electron microscope (SEM) image of the CNTs infused to a fiber material for use in a coating in a solar receiver.

[0024] FIG. **18** shows an exemplary solar receiver.

DETAILED DESCRIPTION

[0025] The present invention is directed, in part, to a solar receiver that incorporates a heat absorbing element having a first coating that includes a carbon nanotube (CNT)-infused fiber material which serves to absorb electromagnetic radiation in a wide spectral range from ultraviolet (UV) at about 200 nm through infrared (IR) at about 2500 nm. The CNTs of the CNT-infused fiber material are good thermal conductors and serve as a conduit for harvesting and converting light energy into heat. CNTs have some of the highest thermal conductivities known for any material with some indications as high as about 6,600 $Wm^{-1} K^{-1}$ (Berber et al. *Phys. Rev. Lett.* 84(20):4613-4616, (2000)).

[0026] Moreover, the fiber material itself of the first coating provides a scaffold to organize the array of infused CNTs with predictable alignments to optimize CNT orientation. CNTs can be fabricated on fiber material substrates in controllably aligned configurations in scalable quantities to provide access to large surface area solar receiver panels. The control of CNT orientation, which is difficult to achieve with "loose" CNT composites, can enhance the light to heat conversion. Control of CNT alignment combined with their high thermal conductivity allows heat to be efficiently and directionally conducted along the CNT length to the heat absorbing element and from the heating element to a heat transfer fluid for use a variety of applications, including energy generation.

[0027] The solar receivers of the present invention can be used in numerous conventional solar heating collector configurations. For example, the solar receivers can operate at relatively low temperatures such as those that can be used in low-end heating applications such as in a swimming pool heating system or agricultural uses such as crop drying. The solar receivers of the present invention can also be used in applications that employ high temperatures, including temperatures that are used in energy generation, such as steam generation, for example. The solar receivers of the present invention can be configured in flat plate designs as well as parabolic designs.

[0028] The coatings employed on solar receivers of the invention can have absorptivity, for example, in the range from between about 0.92 to about 0.99. Moreover, the emissivity of the solar receiver of the invention can be in a range from between about 0.01 to about 0.11. Coatings employed in the solar receivers of the invention can absorb almost all incident radiation in a spectral band from the UV through IR, while transfer to the heating element and subsequently a heat transfer fluid, prevent thermal infra-red emission. It has been indicated that with proper nanotube density, arrays of vertically aligned single-walled CNTs can behave as nearly perfect black body absorbers (Mizuno et al. *Proc. Natl. Acad. Sci.* 106:6044-6047 (2009)). One means to generate a black body absorber is to suppress light reflection, which can be achieved when the refractive index of the object is close to that of air. This solution to minimize reflectance is evident from Fresnel's law:

$$R=(n-n_0)^2/(n+n_0)^2$$

where R is reflectance, n is the refractive index of the object, and n_0 is the refractive index of air. The CNT density on the fiber material can be modulated in the continuous process described herein below. By modulating CNT density, the CNT-infused fiber material can be tuned to exhibit a refractive index, n, that approximates that of air, n_0.

[0029] In some embodiments, the coatings employed in the solar receivers of the invention having CNT-infused fiber material can behave as a black-body-like object and can exhibit high thermal emissivity in the form of black body radiation. In some embodiments, this loss of energy can be reduced or prevented by the channeling of the thermal energy from the CNTs to the heating absorbing element. The heating absorbing element, in turn, heats a heat transfer fluid which can be used, for example, in power generation. Reducing the emissivity of the system can also be achieved by methods known in the art including, for example, employing vacuum glass chambers about the heating element or employing further coating materials, such as anti-reflective coatings or the like.

[0030] In some embodiments, the coatings employed in the solar receivers of the invention having CNT-infused fiber material can behave as intrinsic solar selective materials that absorb nearly all incident light, while have very low emissivity, obviating the need for further coatings, instead efficiently transferring the heat energy to the heat absorbing element and from the heat absorbing element to the heat transfer fluid for use in a variety of applications.

[0031] In some embodiments, a solar receiver includes a heat absorbing element having an outer surface and an inner surface opposite the outer surface. The receiver further includes a carbon nanotube-infused ("CNT-infused") material in a first coating in surface engagement with and at least partially covering the outer surface of the heat absorbing element. CNT-infused fiber material first coatings include, but are not limited to, a CNT-infused fiber material and a CNT-infused fiber material in a matrix forming a composite. The solar radiation incident on the CNT-infused fiber material of the first coating is absorbed, contained, and converted to heat energy. The converted heat energy is transferred from the CNT-infused fiber material of the first coating on the outer surface of the heat absorbing element to the inner surface of the heat absorbing element and is then transferred from the inner surface to a substance such as a heat transfer fluid.

[0032] In some embodiments, a solar receiver includes a heat absorbing element having a plurality of grooves on the surface of the heat absorbing element. In one embodiment, the grooves are on the order of microns (pm) in size and depth. The grooves can be arranged in a spiral configuration along the circumference of the heat absorbing element to form a single groove extending from one end of the heat absorbing element to the other on the outer surface. Such a groove can accommodate, for example, a CNT-infused fiber tow and can provide enhanced surface contact area between the CNT-infused fiber material and the heat absorbing element. Without being bound by theory, this increased surface area contact can provide more efficient heat transfer to the outer surface of the heat absorbing element. In a similar manner, an increased surface area can be provided on the inner surface of the heat absorbing element to increase the efficiency of heat transfer to the heat transfer fluid.

[0033] In some embodiments, a solar receiver includes a low emissivity, environmental coating covering or integrated into the first coating having the CNT-infused fiber material. When integrated into the first coating, it can function as a matrix material to provide a first coating that is a composite structures. The environmental coating allows for the transmission of electromagnetic radiation (at least in ultra-violet to visual range) incident on the outer surface of the environmental coating onto the CNT-infused fiber material of the first coating for absorption and conversion to heat energy. The environmental coating has low emissivity characteristics so as to effectively reduce the emission of heat energy by the CNT-infused coating back to the external environment. The environmental coating can have a low emissivity, particularly, in the infra-red spectrum, corresponding to the spectrum at which the CNT-infused fiber material of the first coating emits heat energy at the system operating temperature.

[0034] In some embodiments, a solar receiver includes an annulus surrounding the heat absorbing element at least partially covered by the first coating having the CNT infused fiber material. In one configuration, the annulus is radially spaced apart from the CNT-infused coating. In an exemplary embodiment, the annulus can include air pockets or air gaps disposed between the annulus and the CNT-infused coating. In another embodiment, the annulus can be evacuated and the gap held under vacuum. The annulus can be coated with one or more of anti-reflective coatings and low emissivity coatings applied to one or both of its outer and inner surfaces. The annulus can further have infrared reflective coating applied to its inner surface which faces the CNT-infused coating.

[0035] As used herein the term "fiber material" refers to any material which has a fiber as its elementary structural component. The term encompasses fibers, filaments, yarns, tows, tows, tapes, woven and non-woven fabrics, plies, mats, and the like. Moreover, the composition of the fiber material can be of any type including, without limitation, glass, carbon, metal, ceramic, organic, or the like.

[0036] As used herein the term "spoolable dimensions" refers to fiber materials having at least one dimension that is not limited in length, allowing for the material to be stored on a spool or mandrel. Fiber materials of "spoolable dimensions" have at least one dimension that indicates the use of either batch or continuous processing for CNT infusion as described herein further below. One exemplary fiber material that is a carbon fiber material of spoolable dimensions is commercially available is exemplified by AS4 12k carbon fiber tow with a tex value of 800 (1 tex=1 g/1,000 m) or 620 yard/lb (Grafil, Inc., Sacramento, Calif.). Commercial carbon fiber tow, in particular, can be obtained in 5, 10, 20, 50, and 100 lb. (for spools having high weight, usually a 3 k/12K tow) spools, for example, although larger spools may require special order. Processes of the invention operate readily with 5 to 20 lb. spools, although larger spools are usable. Moreover, a pre-process operation can be incorporated that divides very large spoolable lengths, for example 100 lb. or more, into easy to handle dimensions, such as two 50 lb spools.

[0037] As used herein, the term "carbon nanotube" (CNT, plural CNTs) refers to any of a number of cylindrically-shaped allotropes of carbon of the fullerene family including single-walled carbon nanotubes (SWNTs), double-walled carbon nanotubes (DWNTs), multi-walled carbon nanotubes (MWNTs). CNTs can be capped by a fullerene-like structure or open-ended. CNTs include those that encapsulate other materials.

[0038] As used herein "uniform in length" refers to length of CNTs grown in a reactor. "Uniform length" means that the CNTs have lengths with tolerances of plus or minus about 20% of the total CNT length or less, for CNT lengths varying from between about 1 micron to about 500 microns. At very short lengths, such as 1-4 microns, this error may be in a range from between about plus or minus 20% of the total CNT length up to about plus or minus 1 micron, that is, somewhat more than about 20% of the total CNT length.

[0039] As used herein "uniform in distribution" refers to the consistency of density of CNTs on a fiber material. "Uniform distribution" means that the CNTs have a density on the fiber material with tolerances of plus or minus about 10% coverage defined as the percentage of the surface area of the fiber covered by CNTs. This is equivalent to ±1500 CNTs/μm^2 for an 8 nm diameter CNT with 5 walls. Such a figure assumes the space inside the CNTs as fillable.

[0040] As used herein, the term "infused" means bonded and "infusion" means the process of bonding. Such bonding can involve direct covalent bonding, ionic bonding, pi-pi, and/or van der Waals force-mediated physisorption. For example, in some embodiments, the CNTs can be directly bonded to the fiber material. Bonding can be indirect, such as the CNT infusion to the fiber material via a barrier coating and/or an intervening transition metal nanoparticle disposed between the CNTs and fiber material. In the CNT-infused fiber materials disclosed herein, the carbon nanotubes can be "infused" to the fiber material directly or indirectly as described above. The particular manner in which a CNT is "infused" to a carbon fiber materials is referred to as a "bonding motif."

[0041] As used herein, the term "transition metal" refers to any element or alloy of elements in the d-block of the periodic table. The term "transition metal" also includes salt forms of the base transition metal element such as oxides, carbides, nitrides, and the like.

[0042] As used herein, the term "nanoparticle" or NP (plural NPs), or grammatical equivalents thereof refers to particles sized between about 0.1 to about 100 nanometers in equivalent spherical diameter, although the NPs need not be spherical in shape. Transition metal NPs, in particular, serve as catalysts for CNT growth on the fiber materials.

[0043] As used herein, the term "matrix material" refers to a bulk material than can serve to organize CNT-infused fiber materials in particular orientations, including random orientation. The matrix material can benefit from the presence of the CNT-infused carbon fiber material by imparting some aspects of the physical and/or chemical properties of the CNT-infused fiber material to the matrix material. In some embodiments, the matrix material can act as the environmental coating that helps retain the heat generated upon absorption of solar radiation by the CNTs. In some embodiments, the matrix material is a ceramic. In some embodiments, the matrix material reflects infrared radiation back to the CNTs preventing heat loss to the environment.

[0044] As used herein, the term "material residence time" refers to the amount of time a discrete point along a fiber material of spoolable dimensions is exposed to CNT growth conditions during the CNT infusion processes described herein. This definition includes the residence time when employing multiple CNT growth chambers.

[0045] As used herein, the term "linespeed" refers to the speed at which a fiber material of spoolable dimensions can be fed through the CNT infusion processes described herein, where linespeed is a velocity determined by dividing CNT chamber(s) length by the material residence time.

[0046] In some embodiments, the present invention provides a solar receiver that includes a heat absorbing element having an outer surface and an inner surface opposite the outer surface; and a first coating that includes a carbon nanotube-infused fiber material in surface engagement with and at least partially covering the outer surface of the heat absorbing element, whereby solar radiation incident onto the first coating is received, absorbed, and converted to heat energy, and the heat energy is transferred from the first coating to said heat absorbing element.

[0047] Solar receivers of the invention can operate low, medium, and high temperature applications as known in the art. High temperature receivers are used in numerous power generating applications, for example, in driving a turbine with steam. High temperature applications can be any application utilizing temperatures greater than about 400° C. Low temperature applications include, for example, pool heating or crop drying. Such temperatures can be about 10-100° C. higher than ambient temperatures. Any applications utilizing temperature between about 100° C. and 400° C. are considered mid temperature applications. Exemplary mid temperature application can include, for example, a parabolic trough or concentrating solar power plant.

[0048] The solar receiver apparatus has a heat absorbing element having a first end and a second end and a heat transfer fluid that enters the heat absorbing element at said first end and exits from the heat absorbing element at the second end. The heat absorbing element can have grooves on the inner and/or outer surface to provide greater surface area contact with the first coating on the outside and/or with the heat transfer fluid on the inside of the heat absorbing element. The first and second ends of the heating element can be used to transport the heat transfer fluid to and from the receiver. The receiver itself is configured to integrate into existing systems and can be incorporated in parabolic and flat panel type receivers.

[0049] The heat absorbing element is generally a heat pipe made of metal, although any conducting material can be used. Moreover, the heat absorbing element need not be cylindrical like a pipe. The heat absorbing element can be any shape and can be chosen for improved surface area on the inner and outer surfaces. For example, in some embodiments, the solar receiver heat absorbing element can have grooves sized to accommodate the CNT-infused fiber material. When the CNT-infused fiber material is a CNT-infused fiber tow, the grooves can be helically disposed on the outer surface of the heating element and the CNT-infused fiber tow wrapped inside the groove and it contact with the wells of the groove. In some embodiments, when a CNT-infused fiber tow is employed, the tow can also be spread onto the heating element.

[0050] In some embodiments, the solar receiver of the invention has a CNT-infused fiber material includes a carbon nanotube-infused fiber tow that includes a material selected from carbon, metal, glass, ceramic and the like.

[0051] In some embodiments, the solar receiver of the invention can further include an environmental coating integrated within said first coating to form a composite. Such materials forming an environmental coating include, without limitation a ceramic matrix material. In some embodiments, the composite formed with the matrix material can further include metal particles. The metal particles can be used to further increase conductive pathways to disperse the heat collected by the CNT infused material. They can serve, for example, as conduits for thermal heat transfer between neighboring CNTs, while serving as a infra-red reflector.

[0052] In some embodiments, the solar receiver of the invention can further include an environmental coating disposed on the first coating, and this environmental coating can include a low-emissivity coating. In such embodiments, the environmental coating can also include the matrix type environmental coating integrated within the CNT-infused fiber material. In some embodiments the environmental coating includes a metal such as copper.

[0053] Solar receivers of the invention can exhibit very low emissivity. Any environmental coating can serve this purpose. Additionally, in some embodiments, the solar receiver of the invention further includes an environmental coating that includes an anti-reflective material. This can be used to reflect infrared heat radiated from the CNTs or the heat absorbing element back towards the CNTs and heating element to prevent heat loss to the environment.

[0054] In still further embodiments, the solar receiver of the invention further includes an annulus surrounding the first coating and the heat absorbing element creating a gap. This gap can include air or the gap can be substantially evacuated.

[0055] The solar receivers of the invention are configured to integrate with a power generation system. In this regard, the overall design of the receiver can be nominally the same as those known in the art.

[0056] In some embodiments, the present invention also provides a multilayer coating for a solar receiver device that includes a first coating having a CNT-infused fiber material; and an environmental coating disposed on the first coating. The first coating further can include a ceramic matrix and the first coating can further include metal particles as described above and herein below.

[0057] The multilayer coating of the invention can include environmental coatings that include a metal film, an anti-reflective coating, and/or a low emissivity coating as described above and further described below.

[0058] It is to be understood that the figures and descriptions of the present invention have been simplified to illustrate elements that are relevant for a clear understanding of the present invention, while eliminating, for purposes of clarity, many other elements found in typical solar receivers and collectors. However, because such elements are well known in the art, and because they do not facilitate a better understanding of the present invention, a discussion of such elements is not provided herein. The disclosure herein is directed to all such variations and modifications known to those skilled in the art.

[0059] Referring to FIG. **1**, there is illustrated a profile view of a solar receiver **100**, according to the first embodiment of the invention. Solar receiver **100** includes a heat absorbing element **110**, and a CNT-infused coating **120** applied to at least a portion of an outer surface **115** of heat absorbing element **110**.

[0060] In one configuration, heat absorbing element **110** is a hollow element adapted to receive a heat transfer substance, for example, a heat transfer fluid therewithin. By way of non-limiting example only, the heat transfer fluid may include water, anti-freeze solution (e.g., water and glycol), air, various gases, oil, and other high temperature (high heat capacity) fluids. In an exemplary embodiment, heat absorbing element **110** is a metallic or alloy absorber tube having a first end **112** and a second end **114**. Heat absorbing element **110** has an outer surface **115** and an inner surface **117** opposite to outer surface **115**. By way of non-limiting examples only, heat absorbing element **110** may be made of stainless steel, carbon steel, or aluminum. One skilled in the art will appreciate that other metals and alloys may also be used. The thickness of heat absorbing element **110** and the material properties of heat absorbing element **110** are selected to efficiently transfer heat from outer surface **115** to inner surface **117** which heats a heat transfer substance present in heat absorbing element **110** generally in surface engagement with inner surface **117**. In an exemplary configuration, an absorber tube may have a length of about 3 meters (m), a diameter of about 70 millimeters (mm), and a wall thickness of about 2 mm. While heat absorber element **110** referred to herein takes the form of a tube or tubular structure, it is understood that heat absorber element **110** may be configured in various geometric forms, including by way of example only, cylindrical, conical, polygonal or other shapes and configurations.

[0061] In one configuration, heat absorbing element **110** is an open system wherein a heat transfer substance such a heat transfer fluid enters at the first end **112** at a first temperature and exits from the second end **114** at a second temperature higher than the first temperature. In another configuration, heat absorbing element **110** may be a closed system, such as a heat pipe, wherein the heat transfer fluid is retained within heat absorbing element **110**. In the illustrated embodiment, heat absorbing element **110** has an outer surface **115**, which is generally uniform.

[0062] Still referring to FIG. **1**, CNT-infused coating **120** is disposed on outer surface **115** of heat absorbing element **110**. CNT-infused coating **120**, therefore, at least partially covers outer surface **115** of heat absorbing element **110**. CNT-infused coating **120** is wound under tension on outer surface **115** of heat absorbing element **110** to establish and maintain an effective surface engagement or contact with outer surface **115** of heat absorbing element **110** while minimizing the gaps therebetween. CNT¬ infused coating **120** receives incident electromagnetic radiation (typically in the form of solar radiation) and converts the received radiation into heat or thermal energy. The converted heat or thermal energy is transferred to outer surface **115** of heat absorber element **110**. In an exemplary embodiment, outersurface **115** of heat absorbing element **110** is substantially completely covered by CNT-infused coating **120**. In another embodiment, one or more pre-defined areas of outer surface **115** may be left uncovered by CNT-infused coating **120**.

[0063] In one configuration, CNT-infused coating **120** takes the form of a glass rope or fiber infused with carbon nanotubes. Other examples of CNT-infused coatings include carbon nanotube-infused fibers and fabrics, such as carbon fibers infused with carbon nanotubes, vapor growth carbon fibers, carbon nanofibers, and graphene. In an exemplary embodiment, CNT-infused coating **120** may have a thickness in the range of about 15 microns (pm) to about 1000 pm. CNT-infused coating **120** may optionally include a matrix of a high temperature cement, resin or epoxy, doped with carbon nanotubes or metal nanoparticles, to provide structural integrity to CNT-infused coating **120**.

[0064] In an exemplary embodiment, CNT-infused coating **120** may be fabricated in the form of glass fibers using in situ carbon nanotube growth techniques. For example, a glass fiber may be fed through a growth chamber maintained at a given temperature of about 5000 to 750° C. Carbon containing feed gas is then introduced into the growth chamber, wherein carbon radicals dissociate and initiate formation of carbon nanotubes on the glass fiber, in presence of catalyst nanoparticles. One such technique is described in the commonly owned Provisional U.S. Application No. 61/155,935, entitled "Low Temperature CNT Growth Using A Gas-Preheat Method," and filed Feb. 27, 2009, which application is incorporated by reference herein in its entirety. Other such methods by which carbon nanotube infused fibers in the form of a composite cover layer or thread or rope layer are to be generated may be utilized to obtain CNT-infused coating **120**.

[0065] As is known in the art, the electromagnetic radiation absorptivity of a carbon nanotube-based structure is, in part, a function of the carbon nanotube length as well as the nanotube volume-filling fraction of the structure. The nanotube volume-filling fraction represents the fraction of the structure's total volume occupied by the nanotubes. In an exemplary embodiment, the nanotube volume-filling fraction of CNT¬ infused coating **120** is in the range of about 0.5% to about 25%. The average spacing between the carbon nanotubes in CNT-infused coating **120** ranges from about 2 nanometers (nm) to about 200 nm. The nanotube volume filling of CNT-infused coating **120** may be tailored by selective positioning of carbon nanotubes therein to control the range of electromagnetic radiation that can be effectively absorbed by CNT-infused coating **120**. The gaps between the nanotubes in CNT-infused coating **120** may be used to selectively capture and absorb radiation having one or more given wavelengths.

[0066] The longer the carbon nanotube in the CNT-infused coating, the higher the absorptivity of electromagnetic radiation (at least in the visible light spectrum). CNT¬ infused coating **120** may include carbon nanotubes having a length in the range of about ten (10) microns to about hundreds of microns.

[0067] As is known in the art, thermal conductivity of a carbon nanotube is dependent upon its structural configuration. In particular, the carbon nanotube has a higher thermal conductivity in the direction of its longitudinal axis as compared with that in a direction perpendicular to its longitudinal axis. In one configuration, CNT-infused coating **120** may, therefore, include carbon nanotubes which are aligned generally perpendicular to outer surface **115**, carbon nanotubes which are aligned generally parallel to outer surface **115** and carbon nanotubes which are aligned neither parallel nor perpendicular to outer surface **115**. Those carbon nanotubes generally perpendicular to outer surface **115** effectively conduct heat converted from the incident radiation to outer surface **115**. Those carbon nanotubes not generally perpendicular to outer surface **115** do not conduct any significant heat to outer surface **115** directly. However, those carbon nanotubes not generally perpendicular to outer surface **115**, form thermal paths to the generally perpendicular carbon nanotubes within CNT-infused coating **120**, thereby increasing overall heat transfer from CNT-infused coating **120** to outer surface **115**. Thus, the alignment of carbon nanotubes in CNT-infused coating **120** may be tailored to maximize the thermal conductivity of CNT-infused coating **120** to heat absorbing element **110**.

[0068] Referring now to FIG. **2**, there is illustrated a solar receiver **200**, according to another embodiment of the invention. Solar receiver **200** is generally similar to solar receiver **100**. However, receiver **200** has a heat absorbing element **110** having grooves **215** formed on outer surface **115**. In one configuration, grooves **215** take the form of a spiral configuration extending along the length of heat absorbing element **110**. It will be appreciated by one skilled in the art that machining a spiral groove is a simple and well known process. In an exemplary embodiment, grooves **215** may have a size ranging from about 50 pm to about 5000 pm. Grooves **215** effectively increase the surface area of outer surface **115** of heat absorbing element **110** exposed to CNT-infused coating **120**. The increased surface area, in turn, increases the effectiveness of heat transfer from CNT-infused coating **120** to outer surface **115** of heat absorbing element **110**. In an exemplary embodiment, grooves **215** are particularly effective when combined with a CNT-infused coating consisting of CNT-infused fiber tows **120**. Groove **215** may be sized to maximize the contact area between interior surface of groove **215** and the outer surface of one or more individual fibers of CNT-infused coating **120**. In an exemplary embodiment, groove **215** may be sized to have a size and depth approximately similar to a CNT-infused fiber of CNT-infused coating **120**, thereby accommodating and seating the CNT-infused fiber of CNT-infused coating **120** in a close fit within groove **215** and maximizing the surface contact between groove **215** and CNT-infused coating **120**. In other embodiments, groove **215** may accommodate a plurality of CNT-infused fibers of CNT-infused coating **120**.

[0069] In one configuration, grooves **215** may take the form of a single groove spirally defined on outer surface **115** and extending continuously along the entire length of absorber element **110**. In another embodiment, grooves **215** may include a series of discontinuous or segmented grooves defined on outer surface **115** of heat absorber element **110**. Such grooves **215** may be aligned longitudinally with one another and sized to accommodate at least a portion of one or more CNT-infused fibers wound about absorber element **110**.

[0070] Referring to FIG. **3**, there is illustrated a solar receiver **300**, according to another embodiment of the invention. Solar receiver **300** is generally similar to solar receiver **100** (of FIG. **1**). In one configuration, an environmental coating **310** may be applied to the top surface of CNT-infused coating **120** to protect CNT-infused coating **120** and to improve the reflective and emissive characteristics of the combination of CNT-infused coating **120** and environmental coating **310**. Several embodiments of environmental coating **310** are schematically depicted in FIGS. **5-12**, and described herein.

[0071] Referring now to FIG. **4**, there is illustrated a solar receiver **400**, according to another embodiment of the invention. Solar receiver **400** is generally similar to solar receiver **200** (of FIG. **2**), further including environmental coating **310** as described for solar receiver **300** (of FIG. **3**).

[0072] Referring now to FIG. **5**, in one configuration of solar receiver **500**, there is shown a ceramic environmental coating **510** integrated with CNT-infused coating **120** for protecting CNT-infused coating **120** from the environment and for reducing the emission of thermal energy from CNT-infused coating **120**. Environmental coating **510** is transparent to at least solar radiation to permit the incident radiation to reach CNT¬ infused coating **120**. Furthermore, environmental coating **510** is reflective of thermal radiation, including infra-red radiation, emitted by CNT-infused coating **120**, thereby reflecting thermal radiation back to CNT-infused coating **120** for reabsorption. Thus, environmental coating **510** has low emissivity characteristics. In an exemplary embodiment, environmental coating **510** may include a ceramic (dielectric) based material applied as a liquid and converted to a glass through a high temperature curing cycle. In another embodiment, environmental coating **510** may be applied through a chemical vapor deposition process, or through plasma sputtering. As such coating application processes are known in the art, they are not described in further detail for the sake of brevity. In one configuration, environmental coating **510** is adapted to withstand high temperatures of CNT-infused coating **120** and heat absorbing element **110**, which may reach as high as 400° to 500° C. In another configuration, environmental coating **510** may be adapted to be hydrophobic to protect CNT-infused coating **120** from environmental moisture. In an exemplary embodiment, environmental coating **510** may have a thickness in the range of about 50 nm to about 500 nm. Examples of materials which may be used to form environmental coating **510** include alumina, silicon dioxide, cesium dioxide, zinc sulfide, aluminum nitride, and zirconium oxide.

[0073] Now referring to FIG. **6**, in another configuration of solar receiver **600**, the integrated ceramic environmental coating **510** and CNT-infused coating **120** is further coated with an anti-reflective coating **615**. The amount of incident radiation lost due to reflectance by the integrated environmental coating **510** and CNT-infused coating **120** may be reduced by disposing anti-reflective coating **615** thereon. Anti-reflective coating **510**, therefore, effectively reduces the reflectance loss of underlying integrated environmental coating **510** and CNT-infused coating **120** and increases the amount of incident radiation absorbed by CNT-infused coating **120**. Examples of such anti-reflective coatings include magnesium fluoride, fluoropolymers and silica-based coatings. The use of such anti-reflective coatings is known in the art and so will not be described in further detail.

[0074] Referring to FIG. **7**, in one configuration of solar receiver **700**, a metallic environmental coating **710** is applied over CNT-infused coating **120**. In an exemplary embodiment, environmental coating **710** may be a metal thin film that is transparent to at least solar radiation to permit the incident radiation to reach CNT-infused coating **120**. Furthermore, environmental coating **710** has low emissivity characteristics, by being reflective of thermal radiation, including infra-red radiation, from CNT-infused coating **120** back to CNT-infused coating **120** for reabsorption. In an exemplary embodiment, environmental coating **710** may include a metal thin film material applied through a chemical vapor deposition process, or through plasma sputtering or spray. In one configuration, environmental coating **710** is adapted to withstand high temperatures of CNT-infused coating **120** and heat absorbing element **110**, which may reach as high as 400° to 500° C. In another configuration, environmental coating **710** may be adapted to be hydrophobic. In an exemplary embodiment, environmental coating **710** may have a thickness in the range of about 1 nm to about 250 nm. Examples of materials which may be used to form environmental coating **510** include, but not limited to, Molybdenum (Mo), Silver (Ag), Copper (Cu), Nickel (Ni), Titanium (Ti), Platinum (Pt), Tungsten (W), Chromium (Cr), Cobalt (Co), Gold (Au), Cupric oxide (CuO), Cobalt oxide (Co304), Molybdenum dioxide (MoO2), Tungsten oxide (WO), titanium oxide (TiO), Titanium nitride (TiN), Iron (Fe), and Ferric oxide (Fe203).

[0075] Referring now to FIG. **8**, in another configuration of solar receiver **800**, metallic environmental coating **710** (of FIG. **7**) is further coated with an anti-reflective coating **615**. Examples of such anti-reflective coatings include magnesium fluoride, fluoropolymers and silica-based coatings.

[0076] Referring to FIG. **9**, in another configuration of solar receiver **900**, the integrated ceramic environmental coating **510** and CNT-infused coating **120** (of FIG. **5**) is further coated with a metal coating **710** (of FIG. **7**), thereby forming a layered cermet coating on heat absorbing element **110**. The layered cermet coating includes metallic coating **710** overlying the integrated ceramic coating **510** and CNT-infused coating **120**. The combination of ceramic layer **510** and metallic layer **710** effectively increases the environmental protection provided to CNT-infused coating **120** and effectively reduces thermal radiation losses from underlying CNT-infused coating **120** by reflecting thermal radiations back to CNT-infused coating **120** for reabsorption. The layered cermet layer provides additional structural integrity to the underlying integrated ceramic coating **510** and CNT-infused coating **120**.

[0077] Referring now to FIG. **10**, in another configuration of solar receiver **1000**, the integrated cermet coatings of FIG. **9** are further coated with an anti-reflective coating **615**. Examples of such anti-reflective coatings include magnesium fluoride, fluoropolymers and silica-based coatings.

[0078] Referring now to FIG. **11**, in another configuration of solar receiver **1100**, the integrated ceramic environmental coating **510** and CNT-infused coating **120** (of FIG. **5**) is doped with metal particles **1110**. In one configuration, particles **1110** may include the metals described for coating **710**, and may be applied via colloidal dispersions or selective plasma sputtering or sprays. Particle sizes may be between several microns to several nanometers. This configuration thus provides an integrated layer of CNT¬ infused coating **120** and integrated ceramic coating **510** doped with metal particles **1110**.

[0079] Referring to FIG. **12**, in another configuration **1200**, the integrated layer of coatings of FIG. **11** is further coated with an anti-reflective coating **615**. Examples of such anti-reflective coatings include magnesium fluoride, fluoropolymers and silica-based coatings.

[0080] Referring now to FIG. **13**, there is illustrated a solar receiver **1300**, according to yet another embodiment of the invention. Solar receiver **1300** is generally similar to solar receiver **300** (of FIG. **3**). Solar receiver **1300** additionally includes an annulus **1310** surrounding heat absorbing element **110** coated with CNT-infused coating **120**. In an exemplary embodiment, annulus **1310** takes the form of a glass annulus. In other embodiments, annulus **1310** may be made of other materials such as quartz or other doped glass materials which are transparent to incident electromagnetic radiation, for example, solar radiation. In one configuration, annulus **1310** may be coated with an anti-reflective coating on its outer surface, inner surface, or both inner and outer surfaces to maximize the amount of incident radiation transmitted through annulus **1310**. In an exemplary embodiment, anti-reflective coating may include multiple thin film structures having alternating layers of contrasting refractive index. Layer thicknesses may be chosen to produce destructive interference in the beams reflected from the interfaces, and constructive interference in the corresponding transmitted beams. Examples of such anti-reflective coatings include magnesium fluoride, fluoropolymers and silica-based coatings.

[0081] In another configuration, annulus **1310** may be additionally or alternatively coated with a low emissivity coating on the outer, inner or both inner and outer surfaces to reduce radiation heat loss from emission from annulus **1310**. In an exemplary embodiment, a low emissivity coating is a thin film metal or metallic oxide layer deposited on annulus **1310**. Non-limiting examples of such low emissivity coatings include Molybdenum (Mo), Silver (Ag), Copper (Cu), and Nickel (Ni) with thicknesses ranging between 500-50 nm. In yet another configuration, annulus **1310** may be additionally or alternatively coated with an infra-red reflective coating on its inner, outer, or both inner and outer surfaces. As is known in the art, heat may be from lost through infra-red radiation from heat absorbing element **110** covered with CNT-infused coating **120**. Annulus **1310** coated with infra-red reflective coating reflect such infra-red radiation, emitted by CNT-infused coating **120**, back to heat absorbing element **110**, where CNT-infused coating **120** re-absorbs such reflected IR radiation. Thus, effective heat loss from infra-red radiation is reduced via reabsorption of the emitted radiation. An example of such an infra-red reflective coating is a cadmium stannate film.

[0082] In an exemplary embodiment, solar receiver **1300** may include air gaps or air pockets between annulus **1310** and heat absorbing element **110** at least partially covered with CNT-infused coating **120**. In another embodiment, annulus **1310** may be evacuated to reduce heat loss due to convection in the air present between CNT¬ infused coating **120** and annulus **1310**. In yet another exemplary embodiment, solar receiver **1300** may further include one or more of the environmental, low emissivity coatings described in relation to FIGS. **5-12**.

[0083] Referring now to FIG. **14**, a solar receiver **1400** is illustrated according to an embodiment of the invention. Solar receiver **1400** is generally similar to solar receiver **400**. Solar receiver **400** additionally includes an annulus **1310** surrounding heat absorbing element **110** at least partially covered with CNT-infused coating **120**. Annulus **1310** may be coated with one or more of anti-reflective coating on its outer, inner or both outer and inner surfaces, low emissivity coating on its outer, inner, or inner and outer surfaces, infra-red radiation reflective coating on its inner, outer, or inner and outer surfaces, as described above herein with regard to the embodiments of FIG. **13**. In yet another exemplary embodiment, solar receiver **1400** may further include one or more of the environmental, low emissivity coatings described in relation to FIGS. **5-12**.

[0084] Below is an exemplary process for generating a CNT infused fiber material. This process is exemplified with carbon fiber material, however, one skilled in the art will appreciate that the operational parameters will be similar for other material types, including glass, ceramic, and metal fiber materials as well.

[0085] In some embodiments the present invention provides a continuous process for CNT infusion that includes (a) disposing a carbon nanotube-forming catalyst on a surface of a fiber material of spoolable dimensions; and (b) synthesizing carbon nanotubes directly on the fiber material, thereby forming a carbon nanotube-infused fiber material. For a 9 foot long system, the linespeed of the process can range from between about 1.5 ft/min to about 108 ft/min. The linespeeds achieved by the process described herein allow the formation of commercially relevant quantities of CNT-infused fiber materials with short production times. For example, at 36 ft/min linespeed, the quantities of CNT-infused fibers (over 5% infused CNTs on fiber by weight) can exceed over 100 pound or more of material produced per day in a system that is designed to simultaneously process **5** separate tows (20 lb/tow). Systems can be made to produce more tows at once or at faster speeds by repeating growth zones. Moreover, some steps in the fabrication of CNTs, as known in the art, have prohibitively slow rates preventing a continuous mode of operation. For example, in a typical process known in the art, a CNT-forming catalyst reduction step can take 1-12 hours to perform. CNT growth itself can also be time consuming, for example requiring tens of minutes for CNT growth, precluding the rapid linespeeds realized in the present invention. The process described herein overcomes such rate limiting steps.

[0086] The CNT-infused fiber material-forming processes of the invention can avoid CNT bundling that occurs when trying to apply suspensions of pre-formed carbon nanotubes to fiber materials. That is, because pre-formed CNTs are not fused to the carbon fiber material, the CNTs tend to bundle and entangle. The result is a poorly uniform distribution of CNTs that weakly adhere to the carbon fiber material. However, processes of the present invention can provide, if desired, a highly uniform entangled CNT mat on the surface of the fiber material by reducing the growth density. The CNTs grown at low density are infused in the fiber material first. In such embodiments, the fibers do not grow dense enough to induce vertical alignment, the result is entangled mats on the carbon fiber material surfaces. By contrast, manual application of pre-formed CNTs does not insure uniform distribution and density of a CNT mat on the carbon fiber material.

[0087] FIG. **15** depicts a flow diagram of process **1500** for producing CNT-infused carbon fiber material in accordance with an illustrative embodiment of the present invention. Again, the use of a carbon fiber material is merely exemplary.

[0088] Process **1500** includes at least the operations of:

[0089] **1501**: Functionalizing the carbon fiber material.

[0090] **1502**: Applying a barrier coating and a CNT-forming catalyst to the functionalized carbon fiber material.

[0091] **1504**: Heating the carbon fiber material to a temperature that is sufficient for carbon nanotube synthesis.

[0092] **1506**: Promoting CVD-mediated CNT growth on the catalyst-laden carbon fiber.

[0093] In step **1501**, the carbon fiber material is functionalized to promote surface wetting of the fibers and to improve adhesion of the barrier coating.

[0094] To infuse carbon nanotubes into a carbon fiber material, the carbon nanotubes are synthesized on the carbon fiber material which is conformally coated with a barrier coating.

[0095] In one embodiment, this is accomplished by first conformally coating the carbon fiber material with a barrier coating and then disposing nanotube-forming catalyst on the barrier coating, as per operation **1502**. In some embodiments, the barrier coating can be partially cured prior to catalyst deposition. This can provide a surface that is receptive to receiving the catalyst and allowing it to embed in the barrier coating, including allowing surface contact between the CNT forming catalyst and the carbon fiber material. In such embodiments, the barrier coating can be fully cured after embedding the catalyst. In some embodiments, the barrier coating is conformally coated over the carbon fiber material simultaneously with deposition of the CNT-form catalyst. Once the CNT-forming catalyst and barrier coating are in place, the barrier coating can be fully cured.

[0096] In some embodiments, the barrier coating can be fully cured prior to catalyst deposition. In such embodiments, a fully cured barrier-coated carbon fiber material can be treated with a plasma to prepare the surface to accept the catalyst. For example, a plasma treated carbon fiber material having a cured barrier coating can provide a roughened surface in which the CNT-forming catalyst can be deposited. The plasma process for "roughing" the surface of the barrier thus facilitates catalyst deposition. The roughness is typically on the scale of nanometers. In the plasma treatment process craters or depressions are formed that are nanometers deep and nanometers in diameter. Such surface modification can be achieved using a plasma of any one or more of a variety of different gases, including, without limitation, argon, helium, oxygen, nitrogen, and hydrogen. In some embodiments, plasma roughing can also be performed directly in the carbon fiber material itself. This can facilitate adhesion of the barrier coating to the carbon fiber material.

[0097] As described further below and in conjunction with FIG. **15**, the catalyst is prepared as a liquid solution that contains CNT-forming catalyst that comprise transition metal nanoparticles. The diameters of the synthesized nanotubes are related to the size of the metal particles as described above. In some embodiments, commercial dispersions of CNT-forming transition metal nanoparticle catalyst are available and are used without dilution, in other embodiments commercial dispersions of catalyst can be diluted. Whether to dilute such solutions can depend on the desired density and length of CNT to be grown as described above.

[0098] With reference to the illustrative embodiment of FIG. **15**, carbon nanotube synthesis is shown based on a chemical vapor deposition (CVD) process and occurs at elevated temperatures. The specific temperature is a function of catalyst choice, but will typically be in a range of about 500 to 1000° C. Accordingly, operation **1504** involves heating the barrier-coated carbon fiber material to a temperature in the aforementioned range to support carbon nanotube synthesis.

[0099] In operation **1506**, CVD-promoted nanotube growth on the catalyst-laden carbon fiber material is then performed. The CVD process can be promoted by, for example, a carbon-containing feedstock gas such as acetylene, ethylene, and/or ethanol. The CNT synthesis processes generally use an inert gas (nitrogen, argon, helium) as a primary carrier gas. The carbon feedstock is provided in a range from between about 0% to about 15% of the total mixture. A substantially inert environment for CVD growth is prepared by removal of moisture and oxygen from the growth chamber.

[0100] In the CNT synthesis process, CNTs grow at the sites of a CNT-forming transition metal nanoparticle catalyst. The presence of the strong plasma-creating electric field can be optionally employed to affect nanotube growth. That is, the growth tends to follow the direction of the electric field. By properly adjusting the geometry of the plasma spray and electric field, vertically-aligned CNTs (i.e., perpendicular to the carbon fiber material) can be synthesized. Under certain conditions, even in the absence of a plasma, closely-spaced nanotubes will maintain a vertical growth direction resulting in a dense array of CNTs resembling a carpet or forest. The presence of the barrier coating can also influence the directionality of CNT growth.

[0101] The operation of disposing a catalyst on the carbon fiber material can be accomplished by spraying or dip coating a solution or by gas phase deposition via, for example, a plasma process. The choice of techniques can be coordinated with the mode with which the barrier coating is applied. Thus, in some embodiments, after forming a solution of a catalyst in a solvent, catalyst can be applied by spraying or dip coating the barrier coated carbon fiber material with the solution, or combinations of spraying and dip coating. Either technique, used alone or in combination, can be employed once, twice, thrice, four times, up to any number of times to provide a carbon fiber material that is sufficiently uniformly coated with CNT-forming catalyst. When dip coating is employed, for example, a carbon fiber material can be placed in a first dip bath for a first residence time in the first dip bath. When employing a second dip bath, the carbon fiber material can be placed in the second dip bath for a second residence time. For example, carbon fiber materials can be subjected to a solution of CNT-forming catalyst for between about 3 seconds to about 90 seconds depending on the dip configuration and linespeed. Employing spraying or dip coating processes, a carbon fiber material with a surface density of catalyst of less than about 5% surface coverage to as high as about 80% coverage, in which the CNT-forming catalyst nanoparticles are nearly monolayer. In some embodiments, the process of coating the CNT-forming catalyst on the carbon fiber material should produce no more than a monolayer. For example, CNT growth on a stack of CNT-forming catalyst can erode the degree of infusion of the CNT to the carbon fiber material. In other embodiments, the transition metal catalyst can be deposited on the carbon fiber material using evaporation techniques, electrolytic deposition techniques, and other processes known to those skilled in the art, such as addition of the transition metal catalyst to a plasma feedstock gas as a metal organic, metal salt or other composition promoting gas phase transport.

[0102] Because processes of the invention are designed to be continuous, a spoolable carbon fiber material can be dip-coated in a series of baths where dip coating baths are spatially separated. In a continuous process in which nascent carbon fibers are being generated de novo, dip bath or spraying of CNT-forming catalyst can be the first step after applying and curing or partially curing a barrier coating to the carbon fiber material. Application of the barrier coating and a CNT-forming catalyst can be performed in lieu of application of a sizing, for newly formed carbon fiber materials. In other embodiments, the CNT-forming catalyst can be applied to newly formed carbon fibers in the presence of other sizing agents after barrier coating. Such simultaneous application of CNT-forming catalyst and other sizing agents can still provide the CNT-forming catalyst in surface contact with the barrier coating of the carbon fiber material to insure CNT infusion.

[0103] The catalyst solution employed can be a transition metal nanoparticle which can be any d-block transition metal as described above. In addition, the nanoparticles can include alloys and non-alloy mixtures of d-block metals in elemental form or in salt form, and mixtures thereof. Such salt forms include, without limitation, oxides, carbides, and nitrides. Non-limiting exemplary transition metal NPs include Ni, Fe, Co, Mo, Cu, Pt, Au, and Ag and salts thereof and mixtures thereof. In some embodiments, such CNT-forming catalysts are disposed on the carbon fiber by applying or infusing a CNT-forming catalyst directly to the carbon fiber material simultaneously with barrier coating deposition. Many of these transition metal catalysts are readily commercially available from a variety of suppliers, including, for example, Ferrotec Corporation (Bedford, N.H.).

[0104] Catalyst solutions used for applying the CNT-forming catalyst to the carbon fiber material can be in any common solvent that allows the CNT-forming catalyst to be uniformly dispersed throughout. Such solvents can include, without limitation, water, acetone, hexane, isopropyl alcohol, toluene, ethanol, methanol, tetrahydrofuran (THF), cyclohexane or any other solvent with controlled polarity to create an appropriate dispersion of the CNT-forming catalyst nanoparticles. Concentrations of CNT-forming catalyst can be in a range from about 1:1 to 1:10000 catalyst to solvent. Such concentrations can be used when the barrier coating and CNT-forming catalyst is applied simultaneously as well.

[0105] In some embodiments heating of the carbon fiber material can be at a temperature that is between about 500° C. and 1000° C. to synthesize carbon nanotubes after deposition of the CNT-forming catalyst. Heating at these temperatures can be performed prior to or substantially simultaneously with introduction of a carbon feedstock for CNT growth.

[0106] In some embodiments, the present invention provides a process that includes removing sizing agents from a carbon fiber material, applying a barrier coating conformally over the carbon fiber material, applying a CNT-forming catalyst to the carbon fiber material, heating the carbon fiber material to at least 500° C., and synthesizing carbon nanotubes on the carbon fiber material. In some embodiments, operations of the CNT-infusion process include removing sizing from a carbon fiber material, applying a barrier coating to the carbon fiber material, applying a CNT-forming catalyst to the carbon fiber, heating the fiber to CNT-synthesis temperature and CVD-promoted CNT growth the catalyst-laden carbon fiber material. Thus, where commercial carbon fiber materials are employed, processes for constructing CNT-infused carbon fibers can include a discrete step of removing sizing from the carbon fiber material before disposing barrier coating and the catalyst on the carbon fiber material.

[0107] The step of synthesizing carbon nanotubes can include numerous techniques for forming carbon nanotubes, including those disclosed in co-pending U.S. Patent Application No. US 2004/0245088 which is incorporated herein by reference. The CNTs grown on fibers of the present invention can be accomplished by techniques known in the art including, without limitation, micro-cavity, thermal or plasma-enhanced CVD techniques, laser ablation, arc discharge, and high pressure carbon monoxide (HiPCO). During CVD, in particular, a barrier coated carbon fiber material with CNT-forming catalyst disposed thereon, can be used directly. In some embodiments, any conventional sizing agents can be removed prior CNT synthesis. In some embodiments, acetylene gas is ionized to create a jet of cold carbon plasma for CNT synthesis. The plasma is directed toward the catalyst-bearing carbon fiber material. Thus, in some embodiments synthesizing CNTs on a carbon fiber material includes (a) forming a carbon plasma; and (b) directing the carbon plasma onto the catalyst disposed on the carbon fiber material. The diameters of the CNTs that are grown are dictated by the size of the CNT-forming catalyst as described above. In some embodiments, the sized fiber substrate is heated to between about 550 to about 800° C. to facilitate CNT synthesis. To initiate the growth of CNTs, two gases are bled into the reactor: a process gas such as argon, helium, or nitrogen, and a carbon-containing gas, such as acetylene, ethylene, ethanol or methane. CNTs grow at the sites of the CNT-forming catalyst.

[0108] In some embodiments, the CVD growth is plasma-enhanced. A plasma can be generated by providing an electric field during the growth process. CNTs grown under these conditions can follow the direction of the electric field. Thus, by adjusting the geometry of the reactor vertically aligned carbon nanotubes can be grown radially about a cylindrical fiber. In some embodiments, a plasma is not required for radial growth about the fiber. For carbon fiber materials that have distinct sides such as tapes, mats, fabrics, plies, and the like, catalyst can be disposed on one or both sides and correspondingly, CNTs can be grown on one or both sides as well.

[0109] As described above, CNT-synthesis is performed at a rate sufficient to provide a continuous process for functionalizing spoolable carbon fiber materials. Numerous apparatus configurations faciliate such continuous synthesis as exemplified below.

[0110] In some embodiments, CNT-infused carbon fiber materials can be constructed in an "all plasma" process. An all plasma process can being with roughing the carbon fiber material with a plasma as described above to improve fiber surface wetting characteristics and provide a more conformal barrier coating, as well as improve coating adhesion via mechanical interlocking and chemical adhesion through the use of functionalization of the carbon fiber material by using specific reactive gas species, such as oxygen, nitrogen, hydrogen in argon or helium based plasmas.

[0111] Barrier coated carbon fiber materials pass through numerous further plasma-mediated steps to form the final CNT-infused product. In some embodiments, the all plasma process can include a second surface modification after the barrier coating is cured. This is a plasma process for "roughing" the surface of the barrier coating on the carbon fiber material to facilitate catalyst deposition. As described above, surface modification can be achieved using a plasma of any one or more of a variety of different gases, including, without limitation, argon, helium, oxygen, ammonia, hydrogen, and nitrogen.

[0112] After surface modification, the barrier coated carbon fiber material proceeds to catalyst application. This is a plasma process for depositing the CNT-forming catalyst on the fibers. The CNT-forming catalyst is typically a transition metal as described above. The transition metal catalyst can be added to a plasma feedstock gas as a precursor in the form of a ferrofluid, a metal organic, metal salt or other composition for promoting gas phase transport. The catalyst can be applied at room temperature in the ambient environment with neither vacuum nor an inert atmosphere being required. In some embodiments, the carbon fiber material is cooled prior to catalyst application.

[0113] Continuing the all-plasma process, carbon nanotube synthesis occurs in a CNT-growth reactor. This can be achieved through the use of plasma-enhanced chemical vapor deposition, wherein carbon plasma is sprayed onto the catalyst-laden fibers. Since carbon nanotube growth occurs at elevated temperatures (typically in a range of about 500 to 1000° C. depending on the catalyst), the catalyst-laden fibers can be heated prior to exposing to the carbon plasma. For the infusion process, the carbon fiber material can be optionally heated until it softens. After heating, the carbon fiber material is ready to receive the carbon plasma. The carbon plasma is generated, for example, by passing a carbon containing gas such as acetylene, ethylene, ethanol, and the like, through an electric field that is capable of ionizing the gas. This cold carbon plasma is directed, via spray nozzles, to the carbon fiber material. The carbon fiber material can be in close proximity to the spray nozzles, such as within about 1 centimeter of the spray nozzles, to receive the plasma. In some embodiments, heaters are disposed above the carbon fiber material at the plasma sprayers to maintain the elevated temperature of the carbon fiber material.

[0114] Another configuration for continuous carbon nanotube synthesis involves a special rectangular reactor for the synthesis and growth of carbon nanotubes directly on carbon fiber materials. The reactor can be designed for use in a continuous in-line process for producing carbon-nanotube bearing fibers. In some embodiments, CNTs are grown via a chemical vapor deposition ("CVD") process at atmospheric pressure and at elevated temperature in the range of about 550° C. to about 800° C. in a multi-zone reactor. The fact that the synthesis occurs at atmospheric pressure is one factor that facilitates the incorporation of the reactor into a continuous processing line for CNT-on-fiber synthesis. Another advantage consistent with in-line continuous processing using such a zone reactor is that CNT growth occurs in a seconds, as opposed to minutes (or longer) as in other procedures and apparatus configurations typical in the art.

[0115] CNT synthesis reactors in accordance with the various embodiments include the following features:

[0116] Rectangular Configured Synthesis Reactors: The cross section of a typical CNT synthesis reactor known in the art is circular. There are a number of reasons for this including, for example, historical reasons (cylindrical reactors are often used in laboratories) and convenience (flow dynamics are easy to model in cylindrical reactors, heater systems readily accept circular tubes (quartz, etc.), and ease of manufacturing. Departing from the cylindrical convention, the present invention provides a CNT synthesis reactor having a rectangular cross section. The reasons for the departure are as follows: 1. Since many carbon fiber materials that can be processed by the reactor are relatively planar such as flat tape or sheet-like in form, a circular cross section is an inefficient use of the reactor volume. This inefficiency results in several drawbacks for cylindrical CNT synthesis reactors including, for example, a) maintaining a sufficient system purge; increased reactor volume requires increased gas flow rates to maintain the same level of gas purge. This results in a system that is inefficient for high volume production of CNTs in an open environment; b) increased carbon feedstock gas flow; the relative increase in inert gas flow, as per a) above, requires increased carbon feedstock gas flows. Consider that the volume of a 12K carbon fiber tow is 2000 times less than the total volume of a synthesis reactor having a rectangular cross section. In an equivalent growth cylindrical reactor (i.e., a cylindrical reactor that has a width that accommodates the same planarized carbon fiber material as the rectangular cross-section reactor), the volume of the carbon fiber material is 17,500 times less than the volume of the chamber. Although gas deposition processes, such as CVD, are typically governed by pressure and temperature alone, volume has a significant impact on the efficiency of deposition. With a rectangular reactor there is a still excess volume. This excess volume facilitates unwanted reactions; yet a cylindrical reactor has about eight times that volume. Due to this greater opportunity for competing reactions to occur, the desired reactions effectively occur more slowly in a cylindrical reactor chamber. Such a slow down in CNT growth, is problematic for the development of a continuous process. One benefit of a rectangular reactor configuration is that the reactor volume can be decreased by using a small height for the rectangular chamber to make this volume ratio better and reactions more efficient. In some embodiments of the present invention, the total volume of a rectangular synthesis reactor is no more than about 3000 times greater than the total volume of a carbon fiber material being passed through the synthesis reactor. In some further embodiments, the total volume of the rectangular synthesis reactor is no more than about 4000 times greater than the total volume of the carbon fiber material being passed through the synthesis reactor. In some still further embodiments, the total volume of the rectangular synthesis reactor is less than about 10,000 times greater than the total volume of the carbon fiber material being passed through the synthesis reactor. Additionally, it is notable that when using a cylindrical reactor, more carbon feedstock gas is required to provide the same flow percent as compared to reactors having a rectangular cross section. It should be appreciated that in some other embodiments, the synthesis reactor has a cross section that is described by polygonal forms that are not rectangular, but are relatively similar thereto and provide a similar reduction in reactor volume relative to a reactor having a circular cross section; c) problematic temperature distribution; when a relatively small-diameter reactor is used, the temperature gradient from the center of the chamber to the walls thereof is minimal. But with increased size, such as would be used for commercial-scale production, the temperature gradient increases. Such temperature gradients result in product quality variations across a carbon fiber material substrate (i.e., product quality varies as a function of radial position). This problem is substantially avoided when using a reactor having a rectangular cross section. In particular, when a planar substrate is used, reactor height can be maintained constant as the size of the substrate scales upward. Temperature gradients between the top and bottom of the reactor are essentially negligible and, as a consequence, thermal issues and the product-quality variations that result are avoided. 2. Gas introduction: Because tubular furnaces are normally employed in the art, typical CNT synthesis reactors introduce gas at one end and draw it through the reactor to the other end. In some embodiments disclosed herein, gas can be introduced at the center of the reactor or within a target growth zone, symmetrically, either through the sides or through the top and bottom plates of the reactor. This improves the overall CNT growth rate because the incoming feedstock gas is continuously replenishing at the hottest portion of the system, which is where CNT growth is most active. This constant gas replenishment is an important aspect to the increased growth rate exhibited by the rectangular CNT reactors.

[0117] Zoning. Chambers that provide a relatively cool purge zone depend from both ends of the rectangular synthesis reactor. Applicants have determined that if hot gas were to mix with the external environment (i.e., outside of the reactor), there would be an increase in degradation of the carbon fiber material. The cool purge zones provide a buffer between the internal system and external environments. Typical CNT synthesis reactor configurations known in the art typically require that the substrate is carefully (and slowly) cooled. The cool purge zone at the exit of the present rectangular CNT growth reactor achieves the cooling in a short period of time, as required for the continuous in-line processing.

[0118] Non-contact, hot-walled, metallic reactor. In some embodiments, a hot-walled reactor is made of metal is employed, in particular stainless steel. This may appear counterintuitive because metal, and stainless steel in particular, is more susceptible to carbon deposition (i.e., soot and by-product formation). Thus, most CNT reactor configurations use quartz reactors because there is less carbon deposited, quartz is easier to clean, and quartz facilitates sample observation. However, Applicants have observed that the increased soot and carbon deposition on stainless steel results in more consistent, faster, more efficient, and more stable CNT growth. Without being bound by theory it has been indicated that, in conjunction with atmospheric operation, the CVD process occurring in the reactor is diffusion limited. That is, the catalyst is "overfed;" too much carbon is available in the reactor system due to its relatively higher partial pressure (than if the reactor was operating under partial vacuum). As a consequence, in an open system—especially a clean one—too much carbon can adhere to catalyst particles, compromising their ability to synthesize CNTs. In some embodiments, the rectangular reactor is intentionally run when the reactor is "dirty," that is with soot deposited on the metallic reactor walls. Once carbon deposits to a monolayer on the walls of the reactor, carbon will readily deposit over itself. Since some of the available carbon is "withdrawn" due to this mechanism, the remaining carbon feedstock, in the form of radicals, react with the catalyst at a rate that does not poison the catalyst. Existing systems run "cleanly" which, if they were open for continuous processing, would produced a much lower yield of CNTs at reduced growth rates.

[0119] Although it is generally beneficial to perform CNT synthesis "dirty" as described above, certain portions of the apparatus, such as gas manifolds and inlets, can nonetheless negatively impact the CNT growth process when soot created blockages. In order to combat this problem, such areas of the CNT growth reaction chamber can be protected with soot inhibiting coatings such as silica, alumina, or MgO. In practice, these portions of the apparatus can be dip-coated in these soot inhibiting coatings. Metals such as INVAR® can be used with these coatings as INVAR has a similar CTE (coefficient of thermal expansion) ensuring proper adhesion of the coating at higher temperatures, preventing the soot from significantly building up in critical zones.

[0120] Combined Catalyst Reduction and CNT Synthesis. In the CNT synthesis reactor disclosed herein, both catalyst reduction and CNT growth occur within the reactor. This is significant because the reduction step cannot be accomplished timely enough for use in a continuous process if performed as a discrete operation. In a typical process known in the art, a reduction step typically takes 1-12 hours to perform. Both operations occur in a reactor in accordance with the present invention due, at least in part, to the fact that carbon feedstock gas is introduced at the center of the reactor, not the end as would be typical in the art using cylindrical reactors. The reduction process occurs as the fibers enter the heated zone; by this point, the gas has had time to react with the walls and cool off prior to reacting with the catalyst and causing the oxidation reduction (via hydrogen radical interactions). It is this transition region where the reduction occurs. At the hottest isothermal zone in the system, the CNT growth occurs, with the greatest growth rate occurring proximal to the gas inlets near the center of the reactor.

[0121] In some embodiments, when loosely affiliated carbon fiber materials, such as carbon tow are employed, the continuous process can include steps that spreads out the strands and/or filaments of the tow. Thus, as a tow is unspooled it can be spread using a vacuum-based fiber spreading system, for example. When employing sized carbon fibers, which can be relatively stiff, additional heating can be employed in order to "soften" the tow to facilitate fiber spreading. The spread fibers which comprise individual filaments can be spread apart sufficiently to expose an entire surface area of the filaments, thus allowing the tow to more efficiently react in subsequent process steps. Such spreading can approach between about 4 inches to about 6 inches across for a 3 k tow. The spread carbon tow can pass through a surface treatment step that is composed of a plasma system as described above. After a barrier coating is applied and roughened, spread fibers then can pass through a CNT-forming catalyst dip bath. The result is fibers of the carbon tow that have catalyst particles distributed radially on their surface. The catalyzed-laden fibers of the tow then enter an appropriate CNT growth chamber, such as the rectangular chamber described above, where a flow through atmospheric pressure CVD or PE-CVD process is used to synthesize the CNTs at rates as high as several microns per second. The fibers of the tow, now with radially aligned CNTs, exit the CNT growth reactor.

[0122] In some embodiments, CNT-infused carbon fiber materials can pass through yet another treatment process that, in some embodiments is a plasma process used to functionalize the CNTs. Additional functionalization of CNTs can be used to promote their adhesion to particular resins. Thus, in some embodiments, the present invention provides CNT-infused carbon fiber materials having functionalized CNTs.

[0123] As part of the continuous processing of spoolable carbon fiber materials, the a CNT-infused carbon fiber material can further pass through a sizing dip bath to apply any additional sizing agents which can be beneficial in a final product. Finally if wet winding is desired, the CNT-infused carbon fiber materials can be passed through a resin bath and wound on a mandrel or spool. The resulting carbon fiber material/resin combination locks the CNTs on the carbon fiber material allowing for easier handling and composite fabrication. In some embodiments, CNT infusion is used to provide improved filament winding. Thus, CNTs formed on carbon fibers such as carbon tow, are passed through a resin bath to produce resin-impregnated, CNT-infused carbon tow. After resin impregnation, the carbon tow can be positioned on the surface of a rotating mandrel by a delivery head. The tow can then be wound onto the mandrel in a precise geometric pattern in known fashion.

[0124] The winding process described above provides pipes, tubes, or other forms as are characteristically produced via a male mold. But the forms made from the winding process disclosed herein differ from those produced via conventional filament winding processes. Specifically, in the process disclosed herein, the forms are made from composite materials that include CNT-infused tow. Such forms will therefore benefit from enhanced strength and the like, as provided by the CNT-infused tow.

[0125] In some embodiments, a continuous process for infusion of CNTs on spoolable carbon fiber materials can achieve a linespeed between about 0.5 ft/min to about 36 ft/min. In this embodiment where the CNT growth chamber is 3 feet long and operating at a 750° C. growth temperature, the process can be run with a linespeed of about 6 ft/min to about 36 ft/min to produce, for example, CNTs having a length between about 1 micron to about 10 microns. The process can also be run with a linespeed of about 1 ft/min to about 6 ft/min to produce, for example, CNTs having a length between about 10 microns to about 100 microns. The process can be run with a linespeed of about 0.5 ft/min to about 1 ft/min to produce, for example, CNTs having a length between about 100 microns to about 200 microns. The CNT length is not tied only to linespeed and growth temperature, however, the flow rate of both the carbon feedstock and the inert carrier gases can also influence CNT length. For example, a flow rate consisting of less than 1% carbon feedstock in inert gas at high linespeeds (6 ft/min to 36 ft/min) will result in CNTs having a length between 1 micron to about 5 microns. A flow rate consisting of more than 1% carbon feedstock in inert gas at high linespeeds (6 ft/min to 36 ft/min) will result in CNTs having length between 5 microns to about 10 microns.

[0126] In some embodiments, more than one carbon material can be run simultaneously through the process. For example, multiple tapes tows, filaments, strand and the like can be run through the process in parallel. Thus, any number of pre-fabricated spools of carbon fiber material can be run in parallel through the process and re-spooled at the end of the process. The number of spooled carbon fiber materials that can be run in parallel can include one, two, three, four, five, six, up to any number that can be accommodated by the width of the CNT-growth reaction chamber. Moreover, when multiple carbon fiber materials are run through the process, the number of collection spools can be less than the number of spools at the start of the process. In such embodiments, carbon strands, tows, or the like can be sent through a further process of combining such carbon fiber materials into higher ordered carbon fiber materials such as woven fabrics or the like. The continuous process can also incorporate a post processing chopper that facilitates the formation CNT-infused chopped fiber mats, for example.

[0127] It is understood that modifications which do not substantially affect the activity of the various embodiments of this invention are also included within the definition of the invention provided herein. Accordingly, the following example is intended to illustrate but not limit the present invention.

Example I

[0128] This example shows the manufacture of CNT infused coating for use in a solar receiver and characterization of a model.

[0129] A CNT based coating can be manufactured by the following procedure:

[0130] CNTs are infused to a carbon fiber tow (carbon fiber being exemplary) in a reel-to-reel system as outlined above. The CNT infused fiber tow is then wrapped over a heating element. Additional reflective layers are added as needed. A coating made by this procedure is expected to exhibit characteristics of being a solar selective coating. The exact characteristics of a coating employing CNT-infused fibers will depend on CNT length and density.

[0131] FIG. **16** shows the reflectivity data for a model of this CNT-infused fiber coating, namely Buckypaper, with an overlay of a theoretical ideal coating indicated as a dashed line. The CNT-infused fiber wrapped around a heating element has an arrangement of CNTs similar to Buckypaper. The arrangement of CNTs in Buckypaper are shown in the SEM image of FIG. **17**.

[0132] The coating having CNT-infused fiber can be formed onto to the outer surface of a heat absorber element for incorporation into a solar receiver, such as the one exemplified in FIG. **18**. This solar receiver includes an annulus surrounding the heat absorbing element coated with CNT-infused coating. The annulus can be borosilicate glass with an anti-reflective coating on its outer surface, inner surface, or both inner and outer surfaces to maximize the amount of incident radiation transmitted through annulus. The annulus can be evacuated to a pressure (less than or equal to 0.0001 Torr) to minimize heat loss due to convection in the air present between CNT-infused coating and annulus.

[0133] While the foregoing invention has been described with reference to the above-described embodiment, various modifications and changes can be made without departing from the spirit of the invention. Accordingly, all such modifications and changes are considered to be within the scope of the appended claims.

What is claimed is:

1. A solar receiver comprising:

a heat absorbing element having an outer surface and an inner surface opposite the outer surface; and

a first coating comprising a carbon nanotube-infused fiber material in surface engagement with and at least partially covering the outer surface of said heat absorbing element;

whereby solar radiation incident onto said first coating is received, absorbed, and converted to heat energy, and the heat energy is transferred from said first coating to said heat absorbing element.

2. The solar receiver apparatus of claim **1**, wherein said heat absorbing element has a first end and a second end, wherein a heat transfer fluid enters said heat absorbing element at said first end and exits from said heat absorbing element at said second end.

3. The solar receiver of claim **1**, wherein said heat absorbing element comprises a heat pipe.

4. The solar receiver of claim **1**, wherein said heat absorbing element comprises a metal.

5. The solar receiver of claim **1**, wherein said heat absorbing element has grooves to sized accommodate said CNT-infused fiber material.

6. The solar receiver of claim **1**, wherein said CNT-infused fiber material comprises a carbon nanotube-infused fiber tow.

7. The solar receiver of claim **1**, further comprising an environmental coating integrated within said first coating to form a composite.

8. The solar receiver of claim **7**, wherein said environmental coating comprises a ceramic matrix material.

9. The solar receiver of claim **7** further comprising metal particles.

10. The solar receiver of claim **1**, further comprising an environmental coating disposed on said first coating, wherein said environmental coating comprises a low-emissivity coating.

11. The solar receiver of claim **1**, further comprising an environmental coating comprising a metal.

12. The solar receiver of claim **1**, further comprising an environmental coating comprising an anti-reflective material.

13. The solar receiver of claim **1**, further comprising an annulus surrounding said first coating and said heat absorbing element creating a gap.

14. The solar receiver of claim **13**, wherein the gap comprises air.

15. The solar receiver of claim **13**, wherein the gap is evacuated.

16. The solar receiver apparatus of claim **1**, wherein said apparatus is configured to integrate with a power generation system.

17. A multilayer coating for a solar receiver device comprising:

a first coating comprising a CNT-infused fiber material; and

an environmental coating disposed on said first coating.

18. The coating of claim **17**, wherein said first coating further comprises a ceramic matrix.

19. The coating of claim **17**, wherein said first coating further comprises metal particles.

20. The coating of claim **17**, wherein said environmental coating comprises a metal film.

21. The coating of claim **17**, wherein said environmental coating comprises an anti-reflective coating.

22. The coating of claim **17**, wherein said environmental coating comprises a low emissivity coating.

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