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(54) **Title**: SPLIT FIBER PRODUCING DEVICES AND METHODS FOR THE PRODUCTION OF MICROFIBERS AND NANOFIBERS

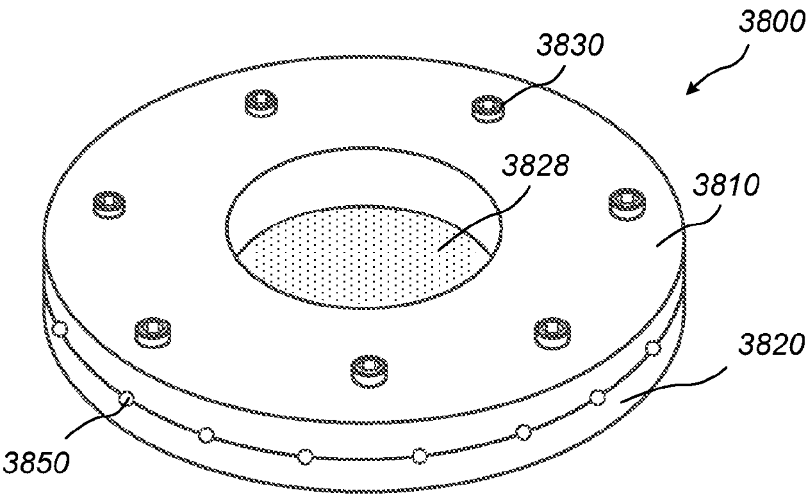

FIG. 11C

(57) **Abstract**: Described herein are apparatuses and methods of creating fibers, such as microfibers and nanofibers. The methods discussed herein employ centrifugal forces to transform material into fibers. Apparatuses that may be used to create fibers are also described. Decsribed herein are fiber producing devices that are composed of two or more members, that, when coupled together, define an internal cavity and a plurality of openings.

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TITLE: SPLIT FIBER PRODUCING DEVICES AND METHODS FOR THE PRODUCTION OF MICROFIBERS AND NANOFIBERS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to the field of fiber production. More specifically, the invention relates to fibers of micron and sub-micron size diameters.

2. Description of the Relevant Art

Fibers having small diameters (e.g., micrometer ("micron") to nanometer ("nano")) are useful in a variety of fields from the clothing industry to military applications. For example, in the biomedical field, there is a strong interest in developing structures based on nanofibers that provide scaffolding for tissue growth to effectively support living cells. In the textile field, there is a strong interest in nanofibers because the nanofibers have a high surface area per unit mass that provide light, but highly wear resistant, garments. As a class, carbon nanofibers are being used, for example, in reinforced composites, in heat management, and in reinforcement of elastomers. Many potential applications for small-diameter fibers are being developed as the ability to manufacture and control their chemical and physical properties improves.

It is well known in fiber manufacturing to produce extremely fine fibrous materials of organic fibers, such as described in U.S. Pat. Nos. 4,043,331 and 4,044,404, where a fibrillar mat product is prepared by electrostatically spinning an organic material and subsequently collecting spun fibers on a suitable surface; U.S. Pat. No. 4,266,918, where a controlled pressure is applied to a molten polymer which is emitted through an opening of an energy charged plate; and U.S. Pat. No. 4,323,525, where a water soluble polymer is fed by a series of spaced syringes into an electric field including an energy charged metal mandrel having an aluminum foil wrapper there around which may be coated with a PTFE (Teflon™) release agent. Attention is further directed to U.S. Pat. Nos. 4,044,404, 4,639,390, 4,657,743, 4,842,505, 5,522,879, 6,106,913 and 6,111,590 – all of which feature polymer nanofiber production arrangements.

Electrospinning is a major manufacturing method to make nanofibers. Examples of methods and machinery used for electrospinning can be found, for example, in the following U.S. Patents: 6,616,435; 6,713,011; 7,083,854; and 7,134,857.

SUMMARY OF THE INVENTION

Described herein are apparatuses and methods of creating fibers, such as microfibers and nanofibers. The methods discussed herein employ centrifugal forces to transform material into fibers. In one embodiment a fiber producing system includes a fiber producing device and a driver capable of rotating the fiber producing device. The fiber producing device, in one embodiment, includes a body having one or more openings and a coupling member, wherein the body is configured to receive material to be produced into a fiber; and one or more nozzles coupled to one or more of the openings, wherein the one or more nozzles comprise a nozzle orifice. The body of the fiber producing device is couplable to the driver through the coupling member. During use rotation of the fiber producing device coupled to the driver causes material in the body to be passed through one or more openings, into one or more nozzles, and ejected through one or more nozzle orifices to produce microfibers and/or nanofibers. In some embodiments, fiber producing system may be configured to substantially simultaneously produce microfibers and nanofibers.

The nozzles of the fiber producing device, in one embodiment, are removably couplable to the body. Alternatively, nozzles of the fiber producing device may be an integral part of the body. A sealing ring may be positioned between one or more of the nozzles and the body to help maintain a secure fitting between the nozzle and the body. In one embodiment, the body includes a locking system used to couple one or more nozzles to the openings, wherein the locking system locks the coupled nozzles in a predetermined orientation with respect to the body.

A nozzle may be removably couplable to a fiber producing device. Alternatively, a nozzle may be formed on a sidewall of the body of the fiber producing device such that the body and nozzle are formed from a single, unitary material. Alternatively, an opening extending through the sidewall may be formed at the junction of a pair of joined circular plates that have an alignment ring or pins. A nozzle may include a nozzle body, the nozzle body defining an internal cavity and having a proximal end and a distal end, wherein the proximal end comprises a coupling portion that allows the nozzle to be coupled to a fiber producing device. The coupling portion of the nozzle, may, in one embodiment, be a threaded end which mates with a corresponding threaded portion of the fiber producing device. A nozzle tip may be coupled to the distal end of the nozzle body, wherein the nozzle tip has an internal diameter that is less than the internal diameter of the nozzle body. The nozzle body includes an opening extending through a wall of the nozzle body, the nozzle tip being aligned with the nozzle opening such that material disposed in the nozzle body passes through the opening into the nozzle tip during use. The internal diameter of the nozzle tip may be set such that microfibers and/or nanofibers are produced when material is ejected through the nozzle tip when the nozzle is coupled to a fiber producing device.

In an embodiment, the nozzle tip and the nozzle body are formed from a single, unitary material. Alternatively, the nozzle tip may be removably couplable to the nozzle body. A nozzle may have a length of at least about 2 mm. An internal diameter of the nozzle tip may be less than about 1 mm. A portion of the interior wall of the nozzle body is substantially flat and another portion of the interior wall of the nozzle body is angled and/or rounded from the flat portion toward the opening formed in the nozzle body. In one embodiment, a nozzle tip may have an angled and/or rounded nozzle outlet end. A nozzle may have a non-cylindrical outer surface. In one embodiment, a nozzle has an outer surface having a tapered edge. During rotation of the body, gasses contact the tapered edge of the nozzle, creating a region of negative pressure on the side opposite to the tapered edge.

One or more outlet conduits may couple one or more nozzles to one or more openings. Outlet conduits may have a length to help set the material diameter before ejection from the nozzle (e.g., from 1mm to about 10mm, or about 2mm to about 7mm, or about 5mm). Nozzles may include a nozzle orifice.

The body of the fiber producing device comprises one or more sidewalls and a top together defining an internal cavity, wherein one or more openings extend through a sidewall of the body, communicating with the internal cavity. In an embodiment, an interior surface of the sidewall is angled from a bottom wall toward one or more of the openings. In an alternate embodiment, an interior surface of the sidewall is rounded from a bottom wall toward one or more of the openings. An interior surface of the sidewall may have an oval shape such that the long axis of the oval interior sidewall is in alignment with one or more of the openings.

The driver may be positioned below the fiber producing device or above the fiber producing device, when the fiber producing device is coupled to the driver. The driver may be capable of rotating the fiber producing device at speeds of greater than about 1000 RPM

In one embodiment, a heating device is thermally coupled to the fiber producing device. In an embodiment, a fluid level sensor is coupled to the fiber producing device, the fluid level sensor being positioned to detect a level of fluid inside the fiber producing device.

The fiber producing device may be enclosed in a chamber, wherein the environment inside the chamber is controllable. A fiber producing system may include a collection system surrounding at least a portion of the fiber producing device, wherein fibers produced during use are at least partially collected on the collection system. The collection system, in one embodiment, includes one or more collection elements coupled to a collection substrate, wherein the one or more collection elements at least partially surround the fiber producing device. In one embodiment, the collection elements comprise an arcuate or straight projection extending from the collection substrate surface.

In another embodiment a fiber producing system includes a fiber producing device and a driver capable of rotating the fiber producing device. The fiber producing device, in one embodiment, includes a body having one or more openings and a coupling member, wherein the body is configured to receive material to be produced into a fiber; and one or more needle ports coupled to one or more of the openings, wherein one or more needles are removably couplable to the needle ports during use. The body of the fiber producing device is couplable to the driver through the coupling member. During use rotation of the fiber producing device coupled to the driver causes material in the body to be ejected through one or more needles coupled to one or more needle ports to produce microfibers and/or nanofibers. In one embodiment, needles coupled to the one or more needle ports have an angled and/or rounded outlet.

In another embodiment a fiber producing system includes a fiber producing device and a driver capable of rotating the fiber producing device. The fiber producing device, in one embodiment, includes a body comprising two or more chambers and a coupling member, wherein a first chamber comprises one or more openings and is configured to receive material to be produced into a fiber; and wherein a second chamber comprises one or more openings and is configured to receive material to be produced into a fiber. The body of the fiber producing device is couplable to the driver through the coupling member. During use, rotation of the fiber producing device coupled to the driver causes material in at least the first chamber and the second chamber to be ejected through the one or more openings to produce microfibers and/or nanofibers.

In another embodiment a fiber producing system includes a fiber producing device and a driver capable of rotating the fiber producing device. The fiber producing device, in one embodiment, includes a body comprising one or more openings and a coupling member, wherein the body is configured to receive material to be produced into a fiber. The body of the fiber producing device is couplable to the driver through the coupling member. The fiber producing system further includes a collection system that collects fibers produced by the fiber producing device during use, the collection system comprising one or more collecting elements coupled to a collection element substrate, wherein one or more collection elements comprise an arcuate projection extending from the collection element substrate. During use, rotation of the body coupled to the driver causes material in the body to be ejected through one or more openings to produce microfibers and/or nanofibers that are at least partially collected on the collecting elements.

In an embodiment, a collection system of a fiber producing system includes one or more collecting elements coupled to a collection element substrate, wherein the collection elements are positioned surrounding at least a portion of the fiber producing device, and wherein the position of the collection elements with respect to the fiber producing device is adjustable by moving the collection elements along a portion of the collection element substrate.

In another embodiment, a collection system of a fiber producing system includes one or more collecting elements coupled to a collection element substrate and a collection container, wherein the collection container at least partially surrounds the fiber producing device and wherein the collection elements are removably positionable in the collection container.

In another embodiment, a collection system of a fiber producing device is configured to collect fibers produced by the fiber producing device. During use rotation of the fiber producing device causes material in the body to be ejected through one or more openings to produce microfibers and/or nanofibers. The collection system produces a vacuum or activated a gas flow device that causes a flow of produced fibers to the collection system.

In another embodiment a fiber producing system includes a fiber producing device and a driver capable of rotating the fiber producing device. The fiber producing device, in one embodiment, includes a body comprising one or more openings and a coupling member, wherein the body is configured to receive material to be produced into a fiber. The body of the fiber producing device is couplable to the driver through the coupling member. The fiber producing system further includes a deposition system that collects fibers produced by the fiber producing device during use and directs the collected fibers toward a substrate disposed in the deposition system during use. During use, rotation of the body coupled to the driver causes material in the body to be ejected through one or more openings to produce microfibers and/or nanofibers that are at least partially transferred to the deposition system.

BRIEF DESCRIPTION OF THE DRAWINGS

Advantages of the present invention will become apparent to those skilled in the art with the benefit of the following detailed description of embodiments and upon reference to the accompanying drawings in which:

FIG. 1A depicts a perspective view of an embodiment of a fiber producing device that includes peripheral openings;

FIG. 1B depicts a cross-sectional side view of an embodiment of a fiber producing device that includes peripheral openings;

FIG. 2 depicts one or more nozzles coupled to one or more openings of a fiber producing device;

FIG. 3 shows a cross-sectional view of the fiber producing device of FIG. 2;

FIG. 4 shows a removably coupleable nozzle, needle port and needle that have been removed from a fiber producing device;

FIG. 5 depicts a cross section view of an embodiment of a nozzle that is couplable to a fiber producing device;

FIG. 6A depicts an alternate embodiment of a fiber producing device;

FIG. 6B depicts cross-section view of an alternate embodiment of a fiber producing device;

FIG. 7 depicts an embodiment of a removably couplable outlet conduit;

FIG. 8 depicts a coaxial outlet element;

FIG. 9 depicts a substrate deposition system;

FIG. 10 depicts a fiber deposition system;

FIGS. 11A-D depict an embodiment of a fiber producing device;

FIG. 12 depicts an embodiment of a heating device;

FIG. 13 depicts an alternate embodiment of a fiber producing device;

FIG. 14A-B depict a star shaped fiber producing device; and

FIG. 15 depicts a gear shaped fiber producing device.

While the invention may be susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and will herein be described in detail. The drawings may not be to scale. It should be understood, however, that the drawings and detailed description thereto are not intended to limit the invention to the particular form disclosed, but to the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

It is to be understood the present invention is not limited to particular devices or methods, which may, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting. As used in this specification and the appended claims, the singular forms “a”, “an”, and “the” include singular and plural referents unless the content clearly dictates otherwise. Furthermore, the word “may” is used throughout this application in a permissive sense (i.e., having the potential to, being able to), not in a mandatory sense (i.e., must). The term “include,” and derivations thereof, mean “including, but not limited to.” The term “coupled” means directly or indirectly connected.

The terms “comprise” (and any form of comprise, such as “comprises” and “comprising”), “have” (and any form of have, such as “has” and “having”), “include” (and any form of include, such as “includes” and “including”) and “contain” (and any form of contain, such as “contains” and “containing”) are open-ended linking verbs. As a method or apparatus that “comprises,” “has,” “includes” or “contains” one or more steps or elements possesses those one or more steps or elements, but is not limited to possessing only those one or more steps or elements. Likewise, an element of an apparatus that “comprises,” “has,” “includes” or “contains” one or more features possesses those one or more features, but is not limited to possessing only those one or more features.

One embodiment of a fiber producing device is shown in FIG. 1A. Fiber producing device **100** includes a top **110** that is coupled to body **120**. Body **120** acts as a reservoir which holds material to be spun into fibers. Top **110** has an opening **112** to allow introduction of material to be spun. For this type of fiber producing device, typical amounts of material range from 50-100 mL, but amounts less than this may be used as well as amounts greater than this, as the size of the reservoir and the fiber producing device may each vary. Body **120** includes one or more openings **122**. A coupling member **160** is coupled to the body. Coupling member **160** may be used to couple fiber producing device **100** to a driver that is capable of rotating the fiber producing device. Coupling member **160** may be an elongated member extending from the body which may be coupled to a portion of the driver (e.g., a chuck or a universal threaded joint of the driver). Alternatively, coupling member may be a receiver which will accept an elongated member from a driver (e.g., the coupling member may be a chuck or a universal threaded joint). Suitable drivers include commercially available variable electric motors, such as a brushless DC motor.

During use, rotation of the fiber producing device causes material to be ejected through one or more openings **122** to produce fibers. In some embodiments, openings **122** may have a size and/or shape that causes the creation of microfibers and/or nanofibers as the material is ejected through the openings.

FIG. 1B depicts a cross-sectional side view of an embodiment of fiber producing device **100**. Body **120** of fiber producing device **100** may further include a tip **124** coupled to one or more openings **122**. Body **120** also defines an internal cavity **140** from which material flows toward openings **122** and, optionally, through tip **124**. In some embodiments, tip **124** has an internal diameter that is less than the diameter of the opening. Tip **124** is coupled to an opening **122** formed in a wall of body **120** such that the tip is substantially aligned with opening. Thus, material disposed in internal cavity **140** passes through opening **122** and through tip **124** when exiting fiber producing device **100**. The internal diameter and/or shape of tip **124** is selected such that microfibers and/or nanofibers are produced when the material is ejected from body **120** of a spinning fiber producing device through the tip. Tip **124** may be removably coupled to body

120. Alternatively, tip **124** and body **120** are formed from a single, unitary material such that the tip is not removable from the body, but instead is an integral part of the body.

In an embodiment depicted in FIG. 2, one or more nozzles **130** may be coupled to one or more openings **122** of fiber producing device **100**. As used herein a "nozzle" is a mechanical device designed to control the direction or characteristics of a fluid flow as it exits (or enters) an enclosed chamber or pipe via an orifice. Nozzles may have an internal cavity **138** running through the longitudinal length of the nozzle, as depicted in FIG. 3. Internal cavity **138** may be substantially aligned with opening **122** when nozzle **130** is coupled to an opening. Spinning of fiber producing device **100** causes material to pass thorough one or more of openings **122** and into one or more nozzles **130**. The material is then ejected from one or more nozzles **130** through nozzle orifice **136** to produce fibers. Nozzle **130** may include a nozzle tip **134** having an internal diameter smaller than an internal diameter of nozzle internal cavity **138**. In some embodiments, internal cavity **138** of nozzle **130** and/or nozzle orifice **136** may have a size and/or shape that causes the creation of microfibers and/or nanofibers by ejecting of the material through the nozzle.

It should be understood that while opposing openings are depicted, the openings may be placed in any position on the body of a fiber producing device. The position of the openings may be varied to create different kinds of fibers. In some embodiments, openings may be placed in different planes of the fiber producing device. In other embodiments, openings may be clustered in certain locations. Such alternate positioning of the openings may increase the fiber dispersion patterns and/or increase the fiber production rates. In some embodiments, the openings, regardless of the position, may accept an outlet element (e.g., a nozzle or needle).

FIG. 3 shows a cross-sectional view of fiber producing device of FIG. 2. Body **120** includes one or more sidewalls **121** and a bottom **123** which together define an internal cavity **125**. In one embodiment, body **120** is substantially circular or oval and includes a singular continuous sidewall **121**, for example, sidewall and bottom are a single, unitary component of the fiber producing device. Openings **122** are formed in sidewall **121** of body **120**, extending through the sidewall such that the opening allows transfer of material from internal cavity **125** through the sidewall. In an embodiment, sidewall **121** is angled from bottom **123** toward one or more openings **122**. Alternatively, sidewall **121** may be rounded from bottom **123** toward one or more openings **122**. Having an angled or rounded sidewall extending toward one or more openings facilitates flow of material in the body toward the openings when the fiber producing device is being rotated. As the fiber producing device is rotated the material rides up the angled or rounded walls toward the openings. This minimizes the occurrence of regions where material is inhibited from traveling toward the openings.

In an embodiment, nozzle(s) **130** may be removably coupled to body **120**. For example, nozzle **130** may include a nozzle coupling portion **132** which is couplable to a corresponding coupling portion **127** of one or more of openings **122**. FIG. 4 shows a removably coupleable nozzle **130** that has been removed from fiber producing device **100**. In this embodiment, nozzle **130** includes a threaded coupling portion **132**, which has threading that matches threading **127** formed in opening **122**. Nozzle **130** may be coupled to body **120** by fastening threaded coupling portion **132** onto threading **127** of opening **122**. Removably coupling a nozzle to a fiber producing device allows removal of the nozzles allowing the ability to customize the production of fibers by allowing the outlet parameters to be changed by changing the nozzle. Additionally clean up of the fiber producing device is improved by allowing the nozzle to be removed and separately cleaned.

FIG. 5 depicts a cross section view of an embodiment of a nozzle **130** that is couplable to a body of a fiber producing device. Nozzle **130** includes a nozzle body **131** having a proximal end **133** and a distal end **135**. Proximal end **133** includes a coupling portion **132** that allows nozzle **130** to be coupled to the body of a fiber producing device. Coupling portion **132** may include a threaded portion which has threading that matches threading formed in an opening of a fiber producing device.

Nozzle **130** further includes a nozzle tip **134** coupled to distal end **135** of the nozzle. Nozzle body **131** defines an internal cavity **138** through which material flows from the body of a fiber producing device toward nozzle orifice **136**. In some embodiments, nozzle tip **134** has an internal diameter that is less than the diameter of internal cavity **138**. Nozzle tip **134** is coupled to an opening **139** formed in a wall of nozzle body **131**. Nozzle tip **134** is aligned with opening **139** such that material disposed in internal cavity **138** passes through opening **139** into the nozzle tip. The internal diameter and/or shape of nozzle tip **134** is selected such that microfibers and/or nanofibers are produced when the material is ejected form the body of a spinning fiber producing device through the nozzle.

Nozzle tip **134** may be removably coupled to nozzle body **131**. Alternatively, nozzle tip **134** and nozzle body **131** are formed from a single, unitary material such that the nozzle tip is not removable from the nozzle body, but instead is an integral part of the nozzle body. Nozzle tip may be angled with respect to nozzle body. In some embodiments, nozzle **130** has a length of at least about 10 mm. In some embodiments, nozzle **130** has a length of between about 5mm to about 15mm. An internal diameter of nozzle **130** may range from about 1.0 mm to about 1mm, depending on the size of fibers to be produced and the viscosity of the material being used to produce the fibers.

To facilitate transfer of material through nozzle **130**, a portion of nozzle body **131** may be angled or rounded toward opening **139**. For example, distal portion **135** of nozzle body **131** may be angled from a flat portion of the nozzle body toward opening **139**. Alternatively, distal portion **135** of nozzle body **131** may be rounded, as depicted in FIG. 5, from a flat portion of the nozzle body toward opening **139**.

In another embodiment, a needle port **140** may be coupled to an opening **122** of body **120**. FIG. 4 depicts an embodiment of a removably couplable needle port that has been removed from fiber producing device **100**. Needle port **140** may include a coupling portion **142** and a needle receiving portion **144**. Needle receiving portion **144** may be used to removably couple a needle to needle port **140**. Coupling portion **142** of needle port **140** is couplable to a corresponding coupling portion **127** of one or more of openings **122**. For example, needle port **140** may include a threaded coupling portion **142**, which has threading that matches threading **127** formed in opening **122**. Needle port **140** may be coupled to body **120** by fastening the threaded coupling portion **142** of the needle port onto threading **127** of opening **122**. Removably coupling a needle port to a fiber producing device allows easy removal of the needle port for clean up. Needle ports offer an additional advantage of allowing customization of the fiber producing device by allowing needles to be removably coupled to the fiber producing device.

In another embodiment, a needle **150** may be coupled to an opening **122** of body **120**. FIG. 4 depicts an embodiment of a removably couplable needle that has been removed from fiber producing device **100**. Needle **150** may include a coupling portion **152**. Coupling portion **152** of needle port **150** is couplable to a corresponding coupling portion **127** of one or more of openings **122**. For example, needle **150** may include a threaded coupling portion **152**, which has threading that matches threading **127** formed in opening **122**. Needle **150** may be coupled to body **120** by fastening the threaded coupling portion **152** of the needle onto threading **127** of opening **122**. Removably coupling a needle to a fiber producing device allows easy removal of the needle for clean up. Having a coupling formed on a needle ports offer an additional advantage of allowing customization of the fiber producing device by allowing needles to be removably coupled to the fiber producing device.

An alternate embodiment of a fiber producing device is shown in FIG. 6A. Fiber producing device **200** includes a top **210** that is coupled to body **220**. Body **220** acts as a reservoir which holds material to be spun into fibers. Top **210** has an opening **212** to allow introduction of material to be spun while the top is fastened to body **220**. Alternatively, top **210** may be removed from body **220** and the material added to the body prior to fastening the top to the body. Body **220** includes one or more openings **222** and a coupling member **260** coupled to the body. Coupling member **260** may be used to couple fiber producing device **200** to a driver that is capable of rotating the fiber producing device. Coupling member **260** may be an elongated member extending from the body which may be coupled to a portion of the driver (e.g., a chuck or a universal threaded joint of the driver). Alternatively, coupling member may be a receiver which will accept an elongated member from a driver (e.g., the coupling member may be a chuck or a universal threaded joint).

One or more needle ports **240** may be coupled to one or more openings **222** via one or more outlet conduits **270**. Outlet conduits **270** may have an annular passageway **272** extending through the longitudinal length of the outlet conduit, as depicted in cross section view FIG. 6B. Outlet conduit **270** may have a length of at least about 10mm, at least about 20 mm, at least about 30 mm, at least about 40 mm, at least about 50 mm, at least about 60 mm inches, or at least about 70 mm. Outlet conduit **270** may have a length of between about 10 mm to about 250 mm, at least about 20 mm to about 200 mm, or at least about 30 mm to about 150mm.

When material is ejected from an opening during spinning of a fiber producing body, the material tends to expand as it leaves an opening. It has been found that by “setting” the diameter of the material prior to the material exiting the fiber producing device, expansion of the material as it leaves the fiber producing device may be minimized. To “set” the diameter of the material annular passageway **272** may have a substantially constant diameter. In some embodiments, the annular passage has a constant diameter of between about 4 mm and about 30 mm over a length of about 10 mm to about 250 mm. Holding the material at a constant diameter over a predetermined length, sets the diameter of the material, reducing the expansion of the material as it exits the outlet conduit and nozzle. Reduction of swelling helps to improve the consistency of the produced fibers with regard to size and length. The length and/or diameter of annular passage **272** may be selected based, at least in part, on the type of material being used. Generally, as the viscosity of the material increases, a longer conduit may be used to properly set the diameter of the material before the material exits the fiber producing device.

In an embodiment, outlet conduits **270** may be removably coupled to body **220**. FIG. 7 depicts an embodiment of a removably couplable outlet conduit **270**. Outlet conduit **270** may include a first coupling portion **274** which is couplable to a complementary coupling portion **227** of a body **220** and a second coupling portion **276** couplable to an outlet element **280**. An outlet element, as used herein includes, but is not limited to, a nozzle, a needle port, a needle or a combination of an outlet conduit coupled to a nozzle, needle port or needle. Outlet element **280** includes a complementary coupling portion **282**, which is couplable to second coupling portion **276** of outlet conduit **270**. An outlet element **280** may be coupled to outlet conduit **270** by mating second coupling portion **276** of the outlet conduit onto coupling portion **282** of the outlet element. Removably coupling an outlet conduit to a body allows easy removal of outlet conduits. Having removably coupled outlet conduits improves the ability to customize the production of fibers by allowing the outlet parameters to be changed by changing the outlet conduit length and diameter as well and the outlet element that is coupled to the outlet conduit. Additionally clean up of the fiber producing device is improved by allowing the outlet conduit to be removed and separately cleaned. Outlet elements such as nozzle **130**, needle port **140** and needle **150**, as depicted in FIG. 4, may be coupled to second coupling portion **276** of outlet conduit **270**.

Fibers represent a class of materials that are continuous filaments or that are in discrete elongated pieces, similar to lengths of thread. Fibers are of great importance in the biology of both plants and animals, e.g., for holding tissues together. Human uses for fibers are diverse. For example, fibers may be spun into filaments, thread, string, or rope. Fibers may also be used as a component of composite materials. Fibers may also be matted into sheets to make products such as paper or felt. Fibers are often used in the manufacture of other materials.

Fibers as discussed herein may be created using, for example, a solution spinning method or a melt spinning method. In both the melt and solution spinning methods, a material may be put into a fiber producing device which is spun at various speeds until fibers of appropriate dimensions are made. The material may be formed, for example, by melting a solute or may be a solution formed by dissolving a mixture of a solute and a solvent. Any solution or melt familiar to those of ordinary skill in the art may be employed. For solution spinning, a material may be designed to achieve a desired viscosity, or a surfactant may be added to improve flow, or a plasticizer may be added to soften a rigid fiber. In melt spinning, solid particles may comprise, for example, a metal or a polymer, wherein polymer additives may be combined with the latter. Certain materials may be added for alloying purposes (e.g., metals) or adding value (such as antioxidant or colorant properties) to the desired fibers.

Non-limiting examples of reagents that may be melted, or dissolved or combined with a solvent to form a material for melt or solution spinning methods include polyolefin, polyacetal, polyamide, polyester, cellulose ether and ester, polyalkylene sulfide, polyarylene oxide, polysulfone, modified polysulfone polymers and mixtures thereof. Non-limiting examples of solvents that may be used include oils, lipids and organic solvents such as DMSO, toluene and alcohols. Water, such as de-ionized water, may also be used as a solvent. For safety purposes, non-flammable solvents are preferred.

In either the solution or melt spinning method, as the material is ejected from the spinning fiber producing device, thin jets of the material are simultaneously stretched and dried or stretched and cooled in the surrounding environment. Interactions between the material and the environment at a high strain rate (due to stretching) leads to solidification of the material into fibers, which may be accompanied by evaporation of solvent. By manipulating the temperature and strain rate, the viscosity of the material may be controlled to manipulate the size and morphology of the fibers that are created. A wide variety of fibers may be created using the present methods, including novel fibers such as polypropylene (PP) nanofibers. Non-limiting examples of fibers made using the melt spinning method include polypropylene, acrylonitrile butadiene styrene (ABS) and nylon. Non-limiting examples of fibers made using the solution spinning method include polyethylene oxide (PEO) and beta-lactams.

The creation of fibers may be done in batch modes or in continuous modes. In the latter case, material can fed continuously into the fiber producing device and the process can be continued over days (e.g., 1-7 days) and even weeks (e.g., 1-4 weeks).

The methods discussed herein may be used to create, for example, nanocomposites and functionally graded materials that can be used for fields as diverse as, for example, drug delivery and ultrafiltration (such as electrets). Metallic and ceramic nanofibers, for example, may be manufactured by controlling various parameters, such as material selection and temperature. At a minimum, the methods and apparatuses discussed herein may find application in any industry that utilizes micro- to nano-sized fibers and/or micro- to nano-sized composites. Such industries include, but are not limited to, material engineering, mechanical engineering, military/defense industries, biotechnology, medical devices, tissue engineering industries, food engineering, drug delivery, electrical industries, or in ultrafiltration and/or micro-electric mechanical systems (MEMS).

Some embodiments of a fiber producing device may be used for melt and/or solution processes. Some embodiments of a fiber producing device may be used for making organic and/or inorganic fibers. With appropriate manipulation of the environment and process, it is possible to form fibers of various configurations, such as continuous, discontinuous, mat, random fibers, unidirectional fibers, woven and nonwoven, as well as fiber shapes, such as circular, elliptical and rectangular (e.g., ribbon). Other shapes are also possible. The produced fibers may be single lumen or multi-lumen.

By controlling the process parameters, fibers can be made in micron, sub-micron and nano-sizes, and combinations thereof. In general, the fibers created will have a relatively narrow distribution of fiber diameters. Some variation in diameter and cross-sectional configuration may occur along the length of individual fibers and between fibers.

Generally speaking, a fiber producing device helps control various properties of the fibers, such as the cross-sectional shape and diameter size of the fibers. More particularly, the speed and temperature of a fiber producing device, as well as the cross-sectional shape, diameter size and angle of the outlets in a fiber producing device, all may help control the cross-sectional shape and diameter size of the fibers. Lengths of fibers produced may also be influenced by the choice of fiber producing device used.

The temperature of the fiber producing device may influence fiber properties, in certain embodiments. Both resistance and inductance heaters may be used as heat sources to heat a fiber producing device. In certain embodiments, the fiber producing device is thermally coupled to a heat source that may be used to adjust the temperature of the fiber producing device before spinning, during spinning, or both before spinning and during spinning. In some embodiments, the fiber producing device is cooled. For example, a fiber producing device may be thermally coupled to a cooling source that can be used to adjust the temperature of the fiber producing device before spinning, during spinning, or before and during spinning. Temperatures of a fiber producing device may range widely. For example, a fiber producing device may be cooled to as low as -20 C or heated to as high as 2500 C. Temperatures below and above these exemplary values are also possible. In certain embodiments, the temperature of a fiber producing device before and/or during spinning is between about 4°C and about 400°C. The temperature of a fiber producing device may be measured by using, for example, an infrared thermometer or a thermocouple.

The speed at which a fiber producing device is spun may also influence fiber properties. The speed of the fiber producing device may be fixed while the fiber producing device is spinning, or may be adjusted while the fiber producing device is spinning. Those fiber producing devices whose speed may be adjusted may, in certain embodiments, be characterized as variable speed fiber producing devices. In the methods described herein, the fiber producing device may be spun at a speed of about 500 RPM to about 25,000 RPM, or any range derivable therein. In certain embodiments, the fiber producing device is spun at a speed of no more than about 50,000 RPM, about 45,000 RPM, about 40,000 RPM, about 35,000 RPM, about 30,000 RPM, about 25,000 RPM, about 20,000 RPM, about 15,000 RPM, about 10,000 RPM, about 5,000 RPM, or about 1,000 RPM. In certain embodiments, the fiber producing device is rotated at a rate of about 5,000 RPM to about 25,000 RPM.

In an embodiment, a method of creating fibers, such as microfibers and/or nanofibers, includes: heating a material; placing the material in a heated fiber producing device; and, after placing the heated material in the heated fiber producing device, rotating the fiber producing device to eject material to create nanofibers from the material. In some embodiments, the fibers may be microfibers and/or nanofibers. A heated fiber producing device is a structure that has a temperature that is greater than ambient temperature. “Heating a material” is defined as raising the temperature of that material to a temperature above ambient temperature. “Melting a material” is defined herein as raising the temperature of the material to a temperature greater than the melting point of the material, or, for polymeric materials, raising the temperature above the glass transition temperature for the polymeric material. In alternate embodiments, the fiber producing device is not heated. Indeed, for any embodiment that employs a fiber producing device that may be heated, the fiber producing device may be used without heating. In some embodiments, the fiber producing device is heated but the material is not heated. The material becomes heated once placed in contact with the heated fiber producing device. In some embodiments, the material is heated and the fiber producing device is not heated. The fiber producing device becomes heated once it comes into contact with the heated material.

A wide range of volumes/amounts of material may be used to produce fibers. In addition, a wide range of rotation times may also be employed. For example, in certain embodiments, at least 5 milliliters (mL) of material are positioned in a fiber producing device, and the fiber producing device is rotated for at least about 10 seconds. As discussed above, the rotation may be at a rate of about 500 RPM to about 25,000 RPM, for example. The amount of material may range from mL to liters (L), or any range derivable therein. For example, in certain embodiments, at least about 50 mL to about 100 mL of the material are positioned in the fiber producing device, and the fiber producing device is rotated at a rate of about 500 RPM to about 25,000 RPM for about 300 seconds to about 2,000 seconds. In certain embodiments, at least about 5 mL to about 100 mL of the material are positioned in the fiber producing device, and the fiber producing device is rotated at a rate of 500 RPM to about 25,000 RPM for 10-500 seconds. In certain embodiments, at least 100 mL to about 1,000 mL of material is positioned in the fiber producing device, and the fiber producing device is rotated at a rate of 500 RPM to about 25,000 RPM for about 100 seconds to about 5,000 seconds. Other combinations of amounts of material, RPMs and seconds are contemplated as well.

Typical dimensions for fiber producing devices are in the range of several inches in diameter and in height. In some embodiments, a fiber producing device has a diameter of between about 1 inch to about 60 inches, from about 2 inches to about 30 inches, or from about 5 inches to about 25 inches. The height of the fiber producing device may range from about 1 inch to about 10 inches, from about 2 inches to about 8 inches, or froom about 3 inches to about 5 inches.

In certain embodiments, fiber producing device includes at least one opening and the material is extruded through the opening to create the nanofibers. In certain embodiments, the fiber producing device includes multiple openings and the material is extruded through the multiple openings to create the nanofibers. These openings may be of a variety of shapes (e.g., circular, elliptical, rectangular, square) and of a variety of diameter sizes (e.g., 0.01-0.80 mm). When multiple openings are employed, not every opening need be identical to another opening, but in certain embodiments, every opening is of the same configuration. Some opens may include a divider that divides the material, as the material passes through the openings. The divided material may form multi-lumen fibers.

In one embodiment, coaxial fibers may be produced using an outlet element having a two or more coaxial conduits. FIG. 8 depicts an outlet element **3200** having an outer conduit **3210** and an inner conduit **3220**. The inner conduit **3220** is sized and positioned inside of the outer conduit **3210** such that the material may flow through the inner conduit and the outer conduit during use. The outlet element **3200** depicted in FIG. 8 may be part of a needle or nozzle (e.g., a nozzle tip). The use of an outlet element **3200** having coaxial conduits allows the formation of coaxial fibers. Different materials may be passed through each of conduits **3210/3220** to produce fibers of mixed materials in which an inner fiber (produced from the inner conduit) is at least partially surrounded by an outer fiber (produced from the outer conduit). The formation of coaxial fibers may allow fibers to be formed having different properties that are selectable based on the materials used to form the fibers. Alternatively, the same material passes through each of conduits **3210/3220** forming a coaxial fiber formed from the same material.

In an embodiment, material may be positioned in a reservoir of a fiber producing device. The reservoir may, for example, be defined by a concave cavity of the heated structure. In certain embodiments, the heated structure includes one or more openings in communication with the concave cavity. The fibers are extruded through the opening while the fiber producing device is rotated about a spin axis. The one or more openings have an opening axis that is not parallel with the spin axis. The fiber producing device may include a body that includes the concave cavity and a lid positioned above the body.

Another fiber producing device variable includes the material(s) used to make the fiber producing device. Fiber producing devices may be made of a variety of materials, including metals (e.g., brass, aluminum, stainless steel) and/or polymers. The choice of material depends on, for example, the temperature the material is to be heated to, or whether sterile conditions are desired.

Any method described herein may further comprise collecting at least some of the microfibers and/or nanofibers that are created. As used herein "collecting" of fibers refers to fibers coming to rest against a fiber collection device. After the fibers are collected, the fibers may be removed from a fiber collection device by a human or robot. A variety of methods and fiber (e.g., nanofiber) collection devices may be used to collect fibers.

Regarding the fibers that are collected, in certain embodiments, at least some of the fibers that are collected are continuous, discontinuous, mat, woven, nonwoven or a mixture of these configurations. In some embodiments, the fibers are not bundled into a cone shape after their creation. In some embodiments, the fibers are not bundled into a cone shape during their creation. In particular embodiments, fibers are not shaped into a particular configuration, such as a cone figuration, using gas, such as ambient air, that is blown onto the fibers as they are created and/or after they are created.

Present method may further comprise, for example, introducing a gas through an inlet in a housing, where the housing surrounds at least the heated structure. The gas may be, for example, nitrogen, helium, argon, or oxygen. A mixture of gases may be employed, in certain embodiments.

The environment in which the fibers are created may comprise a variety of conditions. For example, any fiber discussed herein may be created in a sterile environment. As used herein, the term "sterile environment" refers to an environment where greater than 99% of living germs and/or microorganisms have been removed. In certain embodiments, "sterile environment" refers to an environment substantially free of living germs and/or microorganisms. The fiber may be created, for example, in a vacuum. For example the pressure inside a fiber producing system may be less than ambient pressure. In some embodiments, the pressure inside a fiber producing system may range from about 1 millimeters (mm) of mercury (Hg) to about 700 mm Hg. In other embodiments, the pressure inside a fiber producing system may be at or about ambient pressure. In other embodiments, the pressure inside a fiber producing system may be greater than ambient pressure. For example the pressure inside a fiber producing system may range from about 800 mm Hg to about 4 atmospheres (atm) of pressure, or any range derivable therein.

In certain embodiments, the fiber is created in an environment of 0-100% humidity, or any range derivable therein. The temperature of the environment in which the fiber is created may vary widely. In certain embodiments, the temperature of the environment in which the fiber is created can be adjusted before operation (e.g., before rotating) using a heat source and/or a cooling source. Moreover, the temperature of the environment in which the fiber is created may be adjusted during operation using a heat source and/or a cooling source. The temperature of the environment may be set at sub-freezing temperatures, such as -20°C, or lower. The temperature of the environment may be as high as, for example, 2500°C.

The material employed may include one or more components. The material may be of a single phase (e.g., solid or liquid) or a mixture of phases (e.g., solid particles in a liquid). In some embodiments, the material includes a solid and the material is heated. The material may become a liquid upon heating. In another embodiment, the material may be mixed with a solvent. As used herein a "solvent" is a liquid that at least partially dissolves the material. Examples of solvents include, but are not limited to, water and organic solvents. Examples of organic solvents include, but are not limited to: hexanes, ether, ethyl acetate, acetone, dichloromethane, chloroform, toluene, xylenes, petroleum ether, dimethylsulfoxide, dimethylformamide, or mixtures thereof. Additives may also be present. Examples of additives include, but are not limited to: thinners, surfactants, plasticizers, or combinations thereof.

The material used to form the fibers may include at least one polymer. Polymers that may be used include conjugated polymers, biopolymers, water soluble polymers, and particle infused polymers. Examples of polymers that may be used include, but are not limited to polypropylenes, polyethylenes, polyolefins, polystyrenes, polyesters, fluorinated polymers (fluoropolymers), polyamides, polyaramids, acrylonitrile butadiene styrene, nylons, polycarbonates, beta-lactams, block copolymers or any combination thereof. The polymer may be a synthetic (man-made) polymer or a natural polymer. The material used to form the fibers may be a composite of different polymers or a composite of a medicinal agent combined with a polymeric carrier. Specific polymers that may be used include, but are not limited to chitosan, nylon, nylon-6, polybutylene terephthalate (PBT), polyacrylonitrile (PAN), poly(lactic acid) (PLA), poly(lactic-co-glycolic acid) (PLGA), polyglycolic acid (PGA), polyglactin, polycaprolactone (PCL), silk, collagen, poly(methyl methacrylate) (PMMA), polydioxanone, polyphenylene sulfide (PPS); polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), polypropylene (PP), polyethylene oxide (PEO), acrylonitrile butadiene, styrene (ABS), and polyvinylpyrrolidone (PVP).

In another embodiment, the material used to form the fibers may be a metal, ceramic, or carbon-based material. Metals employed in fiber creation include, but are not limited to, bismuth, tin, zinc, silver, gold, nickel, aluminum, or combinations thereof. The material used to form the fibers may be a ceramic such as alumina, titania, silica, zirconia, or combinations thereof. The material used to form the fibers may be a composite of different metals (e.g., an alloy such as nitonol), a metal/ceramic composite or a ceramic oxides (e.g., PVP with germanium/palladium/platinum).

The fibers that are created may be, for example, one micron or longer in length. For example, created fibers may be of lengths that range from about 1 μm to about 50 cm, from about 100 μm to about 10 cm, or from about 1 mm to about 1 cm. In some embodiments, the fibers may have a narrow length distribution. For example, the length of the fibers may be between about 1 μm to about 9 μm, between about 1 mm to about 9 mm, or between about 1 cm to about 9 cm. In some embodiments, when continuous methods are performed, fibers of up to about 10 meters, up to about 5 meters, or up to about 1 meter in length may be formed.

In certain embodiments, the cross-section of the fiber may be circular, elliptical or rectangular. Other shapes are also possible. The fiber may be a single-lumen fiber or a multi-lumen fiber.

In another embodiment of a method of creating a fiber, the method includes: spinning material to create the fiber; where, as the fiber is being created, the fiber is not subjected to an externally-applied electric field or an externally-applied gas; and the fiber does not fall into a liquid after being created.

Fibers discussed herein are a class of materials that exhibit an aspect ratio of at least 100 or higher. The term “microfiber” refers to fibers that have a minimum diameter in the range of 10 microns to 700 nanometers, or from 5 microns to 800 nanometers, or from 1 micron to 700 nanometers. The term “nanofiber” refers to fibers that have a minimum diameter in the range of 500 nanometers to 1 nanometer; or from 250 nanometers to 10 nanometers, or from 100 nanometers to 20 nanometers.

While typical cross-sections of the fibers are circular or elliptic in nature, they can be formed in other shapes by controlling the shape and size of the openings in a fiber producing device (described below). Fibers may include a blending of multiple materials. Fibers may also include holes (e.g., lumen or multi-lumen) or pores. Multi-lumen fibers may be achieved by, for example, designing one or more exit openings to possess concentric openings. In certain embodiments, such openings may include split openings (that is, wherein two or more openings are adjacent to each other; or, stated another way, an opening possesses one or more dividers such that two or more smaller openings are made). Such features may be utilized to attain specific physical properties, such as thermal insulation or impact absorbance (resilience). Nanotubes may also be created using methods and apparatuses discussed herein.

Fibers may be analyzed via any means known to those of skill in the art. For example, Scanning Electron Microscopy (SEM) may be used to measure dimensions of a given fiber. For physical and material characterizations, techniques such as differential scanning calorimetry (DSC), thermal analysis (TA) and chromatography may be used.

In particular embodiments, a fiber of the present fibers is not a lyocell fiber. Lyocell fibers are described in the literature, such as in U.S. Patent Nos. 6,221,487, 6,235,392, 6,511,930, 6,596,033 and 7,067,444, each of which is incorporated herein by reference.

In one embodiment, microfibers and nanofibers may be produced substantially simultaneously. Any fiber producing device described herein may be modified such that one or more openings has a diameter and/or shape that produces nanofibers during use, and one or more openings have a diameter and/or shape that produces microfibers during use. Thus, a fiber producing device, when rotated will eject material to produce both microfibers and nanofibers. In some embodiments, nozzles may be coupled to one or more of the openings. Different nozzles may be coupled to different openings such that the nozzles designed to create microfibers and nozzles designed to create nanofibers are coupled to the openings. In an alternate embodiment, needles may be coupled (either directly to the openings or via a needle port). Different needles may be coupled to different openings such that needles designed to create microfibers and needles designed to create nanofibers are coupled to the openings. Production of microfibers and nanofibers substantially simultaneously may allow a controlled distribution of the fiber size to be achieved, allowing substantial control of the properties of products ultimately produced from the microfiber/nanofiber mixture.

A top driven fiber producing system is particularly useful for depositing fibers onto a substrate. An embodiment of a system for depositing fibers onto a substrate is shown in FIG. 9. Substrate deposition system **3500** includes a deposition system **3600** and a substrate transfer system **3550**. Deposition system **3600** includes a fiber producing system **3610**, as described herein. Deposition system produces and directs fibers produced by a fiber producing device toward a substrate **3520** disposed below the fiber producing device during use. Substrate transfer system moves a continuous sheet of substrate material through the deposition system.

Deposition system **3600**, in one embodiment, includes a top mounted fiber producing device **3610**. During use, fibers produced by fiber producing device **3610** are deposited onto substrate **3520**. A schematic diagram of deposition system **3600** is depicted in FIG. 10. Fiber deposition system may include one or more of: a vacuum system **3620**, an electrostatic plate **3630**, and a gas flow system **3640**. A vacuum system produces a region of reduced pressure under substrate **3520** such that fibers produced by fiber producing device **3610** are drawn toward the substrate due to the reduced pressure. Alternatively, oneor more fans may be positioned under the substratre to create an air flow through the substrate. Gas flow system **3640** produces a gas flow **3642** that directs fibers formed by the fiber producing device toward the substrate. Gas flow system may be a pressurized air source or one or more fans that produce a flow of air (or other gase). The combination of vacuum and air flow systems are used to produce a "balanced air flow" from the top of the deposition chamber through the substrate to the exhaust system by using forced air (fans, pressurized air) and exhaust air (fans, to create an outward flow) and balancing and directing the airflow to produce a fiber deposition field down to the substrate. Deposition system **3600** includes substrate inlet **3614** and substrate outlet **3612**.

An electrostatic plate **3630** is also positioned below substrate **3520**. The electrostatic plate is a plate capable of being charged to a predetermined polarity. Typically, fibers produced by the fiber producing device have a net charge. The net charge of the fibers may be positive or negative, depending on the type of material used. To improve deposition of charged fibers, an electrostatic plate may be disposed below substrate **3520** and be charged to an opposite polarity as the produced fibers. In this manner, the fibers are attracted to the electrostatic plate due to the electrostatic attraction between the opposite charges. The fibers become embedded in the substrate as the fibers move toward the electrostatic plate.

A pressurized gas producing and distribution system may be used to control the flow of fibers toward a substrate disposed below the fiber producing device. During use fibers produced by the fiber producing device are dispersed within the deposition system. Since the fibers are composed primarily of microfibers and/or nanofibers, the fibers tend to disperse within the deposition system. The use of a pressurized gas producing and distribution system may help guide the fibers toward the substrate. In one embodiment, a pressurized gas producing and distribution system includes a downward gas flow device **3640** and a lateral gas flow device **3645**. Downward gas flow device **3640** is positioned above or even with the fiber producing device to facilitate even fiber movement toward the substrate. One or more lateral gas flow devices **3645** are oriented perpendicular to or below the fiber producing device. In some embodiment, lateral gas flow devices **3645** have an outlet width equal to the substrate width to facilitate even fiber deposition onto substrate. In some embodiments, the angle of the outlet of one or more lateral gas flow devices **3645** may be varied to allow better control of the fiber deposition onto the substrate. Each lateral gas flow devices **3645** may be independently operated.

During use of the deposition system, fiber producing device **3610** may produce various gasses due to evaporation of solvents (during solution spinning) and material gasification (during melt spinning). Such gasses, if accumulated in the deposition system may begin to effect the quality of the fiber produced. In some embodiment, the deposition system includes an outlet fan **3650** to remove gasses produced during fiber production from the deposition system.

Substrate transfer system **3550**, in one embodiment, is capable of moving a continuous sheet of substrate material through the deposition system. In one embodiment, substrate transfer system **3550** includes a substrate reel **3552** and a take up reel system **3554**. During use, a roll of substrate material is placed on substrate reel **3552** and threaded through deposition system **3600** to the substrate take up reel system **3554**. During use, substrate take up reel system **3554** rotates, pulling substrate through deposition system at a predetermined rate. In this manner, a continuous roll of a substrate material may be pulled through fiber deposition system.

An embodiment of a fiber producing device is depicted in FIGS. 11A-C. Fiber producing device **3800** includes a body comprising a first member **3810** (FIG. 11A) and a second member **3820** (FIG. 11B). First member **3810** includes a first member coupling surface **3812**. First member coupling surface **3812** includes one or more grooves **3814** extending along the width of the first member coupling surface. Second member **3820** includes a second member coupling surface **3822** and a coupling member **3828**. Second member coupling surface **3822** comprising one or more grooves **3824** extending along the width of the second member coupling surface. Coupling member **3828** may be used to couple the body to a driver of a fiber producing system.

The body is formed by coupling first member **3810** to second member **3820**. To couple the first and second members, first member coupling surface **3812** is contacted with second member coupling surface **3822**. One or more fasteners **3830** may be used to secure the first member and second member together. When the first member coupling surface is coupled to the second member coupling surface to form the body, the first member and the second member together define an internal cavity of the body. In one embodiment, fasteners **3830** have an effect on the pattern of fiber produced by the fiber producing device. For example, the head of a fastener produces external gas currents due to the high speed of rotation of the fiber producing device. Additional components may be added on either side of the body or incorporated directly onto the surface of the body to produce external gas currents. These external gas currents can effect the pattern of fibers produced. The pattern of fibers produced by the fiber producing device may be altered by using fasteners having different head configurations. Alternatively, the position of fasteners may be altered to change the fiber deposition pattern. For example, the one or more fasteners may be left out of existing holes. Alternatively, the body may include a plurality of holes. The pattern of fibers produced by the fiber producing device may be altered by changing which of the plurality of holes are used to couple the first and second members together. In another embodiment,. The height of the fasteners may be altered by loosing and or tightening the fasteners. Thus the height of the head of one or more fasteners may be varied to alter the pattern of fibers produced by the fiber producing device.

In some embodiments, it is desirable that grooves **3814** of the first member are substantially aligned with groves **3824** of the second member. When the grooves are aligned, the grooves together form one or more openings **3850** extending from the interior cavity to an outer surface of the body. During use, rotation of the body material disposed in the internal cavity of the body is ejected through one or more openings **3850** to produce microfibers and/or nanofibers. Material may be placed into the body of fiber producing through a first member opening **3828** formed in first member **3810**. In one embodiment, first member is ring shaped and material is added to the internal cavity through a central opening of the ring shaped first member.

In order to ensure proper alignment of the first member with the second member, the first member may include a first alignment element **3816** disposed on the first coupling member surface **3812**. The second member may include a second alignment element **3826** disposed on the second member coupling surface **3822**. First alignment element **3816** couples with second alignment element **3826** when first member **3810** is properly aligned with second member **3820**. This may help to ensure that grooves **3814** and **3824** are properly aligned. In one embodiment, one of the first or second alignment elements includes a projection extending form the coupling surface, and the other of the first or second alignment elements includes an indentation complementary to the projection.

In an embodiment, the first alignment element may be a first alignment ring **3816** disposed on the first coupling member surface **3812**. The second member may include a second alignment ring **3826** disposed on the second member coupling surface **3822**. First alignment ring **3816** interlocks with second alignment ring **3826** when first member **3810** is properly aligned with second member **3820**. The interlocking first and second rings center the first member and second member with each other. In one embodiment, first and second rings interlock with each other on an angle so that the first and second members are centered to one another. Alignment is further insured by the use of a projection **3840** formed in the first member which fits into a suitable indentation **3845** formed in the second member. Projection **3840** and indentation **3845** help ensure that the first and second members are coupled in the same rotational position such that the grooves of the first and second members are aligned.

In an embodiment, where the fiber producing device is coupled to a driver positioned above the fiber producing device, the coupling member extends through the internal cavity defined by the first and second members and through the first member. Alternatively, where the fiber producing device is coupled to a driver positioned below the fiber producing device, the coupling member is coupled to an outer surface of the second member, extending away from the second member.

An embodiment of a multiple layer fiber producing device is depicted in FIG. 11D. Fiber producing device **3800** includes a body comprising a first member **3810**, a second member **3820,** and a third member **3830**. It should be understood that while three members are shown, any number of members may be coupled together to form a multiple layer fiber producing device. The body is formed by coupling first member **3810** to second member **3820** and second member to third member **3830**. Second member includes a second member coupling surface and an additional coupling surface, disposed on the side opposite to the second member coupling surface. Both the second member coupling surface and the second member additional coupling surface include grooves extending along the width of the respective surfaces. First and second members couple together by contacting first member coupling surface with the second member coupling surface. Grooves of the first member are substantially aligned with groves of the second member to form one or more openings **3850** extending from the interior cavity to an outer surface of the body. Second and third members also couple together by contacting the second member additional coupling surface with the third member coupling surface. Grooves of the second member additional coupling surface are substantially aligned with groves of the third member coupling surface to form one or more openings **3850** extending from the interior cavity to an outer surface of the body.

During use, material disposed in the internal cavity of the body is ejected through one or more openings **3850** and one or more openings **3855** to produce microfibers and/or nanofibers. Material may be placed into the body of fiber producing through a first member opening formed in first member **3828**. In one embodiment, material is added to the internal cavity through a central opening of the first member.

An embodiment of a heating device **3900** is depicted in FIG. 12. One or more heating elements **3910** are coupled to a heating device substrate **3920**. Heating substrate **3920** is formed of a thermally conductive material (e.g., stainless steel, iron, etc.). Heating elements **3910** may provide heat to heat substrate **3920**. Substrate **3920** is thermally coupled to one or more components of a fiber producing system (e.g., a fiber producing device). In one embodiment, heating elements **3910** may be cartridge heaters that are disposed within substrate **3920**. For example, one or more openings may be formed in substrate **3920** and the cartridge heaters disposed in the openings. During use, an electric current may be applied to one or more of the cartridge heaters to heat the substrate. While the heating device is depicted as having a ring shaped substrate, it should be understood that other shapes may be used.

In an alternate embodiments, a heating device used to heat a fiber producing device is a radiant heater. An infrared heater is an example of a radiant heater that may be used to heat a fiber producing device.

An embodiment of a fiber producing device is depicted in FIG. 13. Fiber producing device **4000** includes a body comprising a first member **4010** and a second member **4020**. The body is formed by coupling first member **4010** to second member **4020**. First and second members couple together by contacting first member coupling surface with second member coupling surface. In some embodiments, it is desirable that grooves of the first member are substantially aligned with groves of the second member. When the grooves are aligned, the grooves together form one or more openings **4050** extending from the interior cavity to an outer surface of the body. During use, rotation of the body material disposed in the internal cavity of the body is ejected through one or more openings **4050** to produce microfibers and/or nanofibers. Material may be placed into the body of fiber producing through a first member opening formed in first member **4010**. In one embodiment, first member is ring shaped and material is added to the internal cavity through a central opening of the ring shaped first member.

One or more fasteners **4030** may be used to secure the first member and second member together. When the first member coupling surface is coupled to the second member coupling surface to form the body, the first member and the second member together define an internal cavity of the body. One or more channels **4028** may be added on either side of the body surrounding openings **4050** and extending away fro the openings. Channels **4028** help alter the external gas currents produced when the spinneretet is spinning. These external gas currents can effect the pattern of fibers produced and/or the size of the fibers produced. The pattern of fibers produced by the fiber producing device may be altered by using channels having different sizes and/or shapes. In some embodiments, channels **4028** are concave channels that allow the fiber producing material ejected from the openings to run along the channel and be ejected at an angle away from the body.

Fiber producing devices may be formed in different shapes. Non-limiting examples of fiber producing devices having alternate shapes are depicted in FIGS. 14A-B and FIG. 15. In an embodiment depicted in FIG. 14A, fiber producing device **4100** includes a body that is in the form of a star. The body of the fiber producing device is composed of a first member **4110** and a second member **4120**, as depicted in FIG. 14B. The body is formed by coupling first member **4110** to second member **4120**. First and second members couple together by contacting first member coupling surface with second member coupling surface. In some embodiments, it is desirable that grooves of the first member are substantially aligned with groves of the second member. When the grooves are aligned, the grooves together form one or more openings **4150** extending from the interior cavity to an outer surface of the body. During use, rotation of the body material disposed in the internal cavity of the body is ejected through one or more openings **4150** to produce microfibers and/or nanofibers. Material may be placed into the body of fiber producing through a first member opening formed in first member **3810**. In one embodiment, material is added to the internal cavity through a central opening **4140** of the first member. In some embodiments, each arm of fiber producing device **4100** may have an aerodynamic profile. The use of an aerodynamic profile may reduce drag forces on the fiber producing device as the device is spun during use. Additionally, the profile of the arms may be adjusted to control the physical properties of the fibers being produced.

In another embodiment, a gear shaped fiber producing device, as depicted in FIG. 15 may be used to produce nanofibers and/or microfibers. Gear shaped fiber producing device **4200** may be formed from a single unitary device, or from two or more sperate pieces that are coupled together as had been described above. Fiber producing device **4200** includes a plurality of protruding segments **4230** extending from central body **4210**. Each segment **4230** is defined by sidewalls **4232** and **4234**. Sidewalls **4232** are substantially straight, while sidewalls **4234** are curved. The segments **4230** are positioned such that the straight sidewalls **4232** of a segment are postioned across from the curved sidewall of an adjacent segment **4234**. Thus a gap is formed between the segments having a curved and straight boundary.

In contrast to other fiber producing devices, openings **4250** are formed in between the protruding segments **4230**, rather than at the end of the segments. During use, material disposed in the body of fiber producing device **4200** is ejected through openings **4250**. When the fiber producing device is rotating, the material exits openings **4250** and is carried to the curved sidewalls **4234**. The material runs along the curved sidewalls and is ejected from the fiber producing device. The amount of arc on curved sidewalls **4234** may be adjusted to alter the size and/or direction that the fibers are produced.

Applications

Microfibers and nanofibers produced using any of the devices and methods described herein may be used in a variety of applications. Some general fields of use include, but are not limited to: food, materials, electrical, defense, tissue engineering, biotechnology, medical devices, energy, alternative energy (e.g., solar, wind, nuclear, and hydroelectric energy); therapeutic medicine, drug delivery (e.g., drug solubility improvement, drug encapsulation, etc.); textiles/fabrics, nonwoven materials, filtration (e.g., air, water, fuel, semiconductor, biomedical, etc); automotive; sports; aeronautics; space; energy transmission; papers; substrates; hygiene; cosmetics; construction; apparel, packaging, geotextiles, thermal and acoustic insulation.

Some products that may be formed using microfibers and/or nanofibers include but are not limited to: filters using charged nanofiber and/or microfiber polymers to clean fluids; catalytic filters using ceramic nanofibers ("NF"); carbon nanotube ("CNT") infused nanofibers for energy storage; CNT infused/coated NF for electromagnetic shielding; mixed micro and NF for filters and other applications; polyester infused into cotton for denim and other textiles; metallic nanoparticles or other antimicrobial materials infused onto/coated on NF for filters; wound dressings, cell growth substrates or scaffolds; battery separators; charged polymers or other materials for solar energy; NF for use in environmental clean-up; piezoelectric fibers; sutures; chemical sensors; textiles/fabrics that are water & stain resistant, odor resistant, insulating, self-cleaning, penetration resistant, anti-microbial, porous/breathing, tear resistant, and wear resistant; force energy absorbing for personal body protection armor; construction reinforcement materials (e.g., concrete and plastics); carbon fibers; fibers used to toughen outer skins for aerospace applications; tissue engineering substrates utilizing aligned or random fibers; tissue engineering Petri dishes with aligned or random nanofibers; filters used in pharmaceutical manufacturing; filters combining microfiber and nanofiber elements for deep filter functionality; hydrophobic materials such as textiles; selectively absorbent materials such as oil booms; continuous length nanofibers (aspect ratio of more than 1,000 to 1); paints/stains; building products that enhance durability, fire resistance, color retention, porosity, flexibility, anti microbial, bug resistant, air tightness; adhesives; tapes; epoxies; glues; adsorptive materials; diaper media; mattress covers; acoustic materials; and liquid, gas, chemical, or air filters.

Fibers may be coated after formation. In one embodiment, microfibers and/or nanofibers may be coated with a polymeric or metal coating. Polymeric coatings may be formed by spray coating the produced fibers, or any other method known for forming polymeric coatings. Metal coatings may be formed using a metal deposition process (e.g., CVD).

In this patent, certain U.S. patents, U.S. patent applications, and other materials (e.g., articles) have been incorporated by reference. The text of such U.S. patents, U.S. patent applications, and other materials is, however, only incorporated by reference to the extent that no conflict exists between such text and the other statements and drawings set forth herein. In the event of such conflict, then any such conflicting text in such incorporated by reference U.S. patents, U.S. patent applications, and other materials is specifically not incorporated by reference in this patent.

Further modifications and alternative embodiments of various aspects of the invention will be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the general manner of carrying out the invention. It is to be understood that the forms of the invention shown and described herein are to be taken as examples of embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed, and certain features of the invention may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description of the invention. Changes may be made in the elements described herein without departing from the spirit and scope of the invention as described in the following claims.

WHAT IS CLAIMED IS:

1. A device for use in a microfiber and/or nanofiber producing system, the device comprising:

a body comprising a first member and a second member, the first member comprising a first member coupling surface, the first member coupling surface comprising one or more grooves extending along the width of the first member coupling surface, the second member comprising a second member coupling surface and a coupling member, the second member coupling surface comprising one or more grooves extending along the width of the second member coupling surface, wherein the body is couplable to a driver through the coupling member;

wherein the first member coupling surface is coupled to the second member coupling surface to form the body, wherein the first member and the second member together define an internal cavity of the body; and

wherein one or more grooves of the first member coupling member are substantially aligned with one or more grooves of the second member coupling member to form one or more openings extending from the interior cavity to an outer surface of the body;

wherein, during use, rotation of the body causes material in the body to be ejected through one or more openings to produce microfibers and/or nanofibers.

2. The device of claim 1, further comprising:

a third member comprising a third member coupling surface, the third member coupling surface comprising one or more grooves extending along the width of the third member coupling surface, the second member comprising an additional coupling surface comprising one or more grooves extending along the width of the second member coupling surface, wherein the body is couplable to a driver through the coupling member;

wherein the third member coupling surface is coupled to the additional coupling surface of the second member to form a portion of the body, wherein the first member, the second member, and the third member together define an internal cavity of the body; and wherein one or more grooves of the third member coupling surface are substantially aligned with one or more grooves of the additional coupling surface of second member to form one or more openings extending from the interior cavity to an outer surface of the body.

3. The device of claim 1 or 2, wherein the body is cylindrical.

4. The device of any one of claims 1-3, wherein the first member comprises a first member opening, wherein material is added to the internal cavity through the first member opening.

5. The device of any one of claims 1-4, wherein the first member is secured to the second member using one or more fasteners.

6. The device of any one of claims 1-5, wherein an interior surface of a sidewall of the internal cavity is rounded from a bottom wall toward one or more of the openings.

7. The device of any one of claims 1-6, further comprising a first alignment element disposed on the first coupling surface and a second alignment element disposed on the second coupling surface, wherein the first alignment element couples with the second alignment element when the first member is properly aligned with the second member.

8. The device of claim 7, wherein one of the first or second alignment elements comprises a projection extending form the coupling surface, and wherein the other of the first or second alignment elements comprises an indentation complementary to the projection.

9. A microfiber and/or nanofiber producing system comprising:

a fiber producing device as decribed in any one of claims 1-8;

a driver capable of rotating the fiber producing device, wherein the body of the fiber producing device is couplable to the driver through the coupling member; and wherein, during use, rotation of the body causes material in the body to be ejected through one or more openings to produce microfibers and/or nanofibers.

10. A method of producing microfibers and/or nanofibers, comprising:

placing material in a fiber producing device as described in any one of claims 1-9;

rotating the fiber producing device at a speed of at least about 1000 rpm, wherein rotation of the fiber producing device causes material in the body to be ejected through one or more openings to produce microfibers and/or nanofibers; and

collecting at least a portion of the produced microfibers and/or nanofibers.

11. The method of claim 10, wherein the microfibers and/or nanofibers are created without subjecting the fibers, during their creation, to an externally applied electric field.

12. The method of claim 10, further comprising:

heating the material to a temperature sufficient to at least partially melt the material;

heating the fiber producing device to a temperature at or near the temperature sufficient to at least partially melt the material; and

placing the heated material in the heated fiber producing device.

13. The method of claim 10, further comprising:

placing material in a fiber producing device; and

heating the fiber producing device to a temperature at or near the temperature sufficient to at least partially melt the material disposed in the fiber producing device.

14. The method of claim 10, further comprising mixing the material with a solvent to produce a mixture of the material in a solvent, and placing the mixture in the fiber producing device.

15. A method of making a device as claimed in any one of claims 1-9 for use in a microfiber and/or nanofiber producing system, the method comprising:

obtaining a first member, the first member comprising a first member coupling surface, the first member coupling surface comprising one or more grooves extending along the width of the first member coupling surface;

obtaining a second member, the second member comprising a second member coupling surface and a coupling member, the second member coupling surface comprising one or more grooves extending along the width of the second member coupling surface;

coupling the first member coupling surface to the second member coupling surface to form a body, wherein the first member and the second member together define an internal cavity of the body; and

wherein one or more grooves of the first member coupling member are substantially aligned with one or more grooves of the second member coupling member to form one or more openings extending from the interior cavity to an outer surface of the body;

wherein, during use, rotation of the body causes material in the body to be passed through one or more openings to produce microfibers and/or nanofibers.

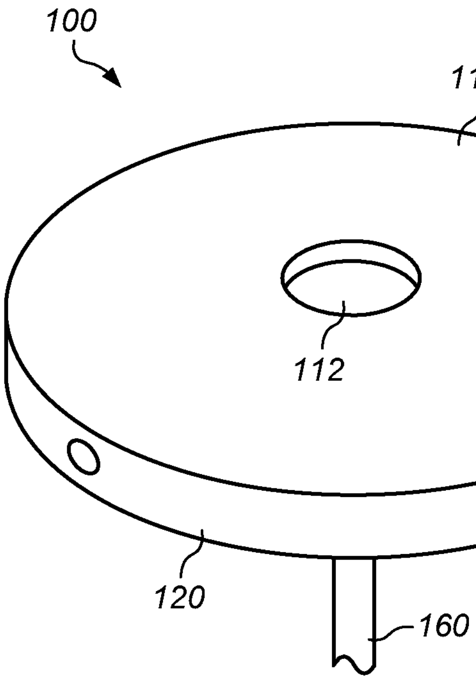

FIG. 1A

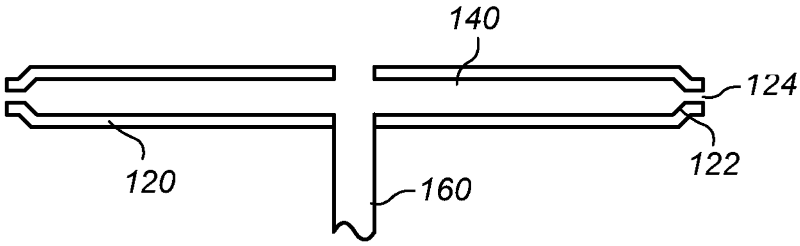

FIG. 1B

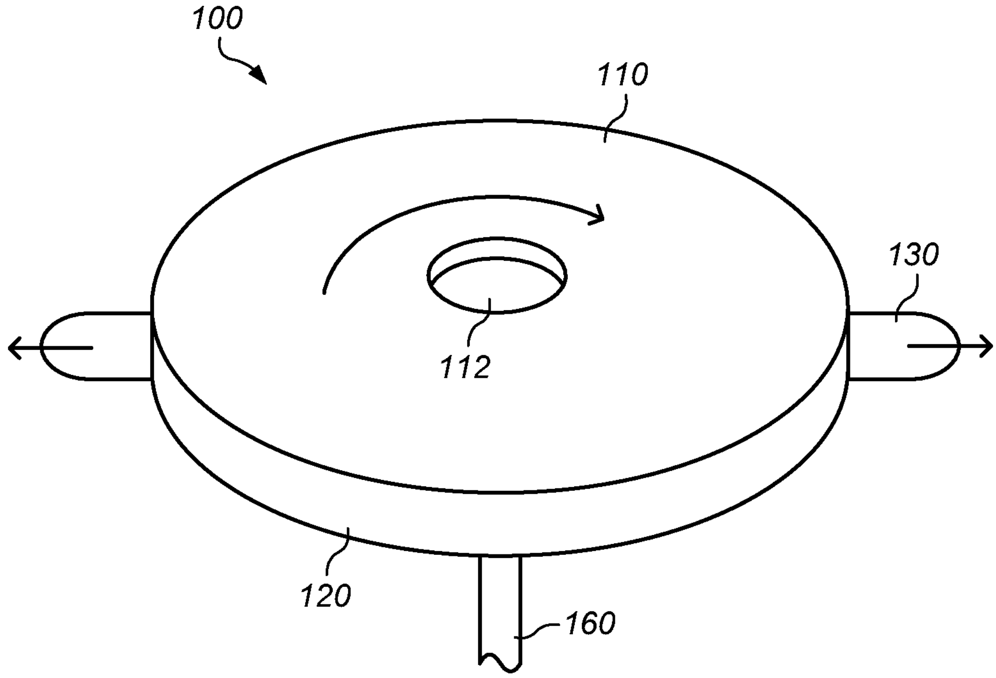
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FIG. 2

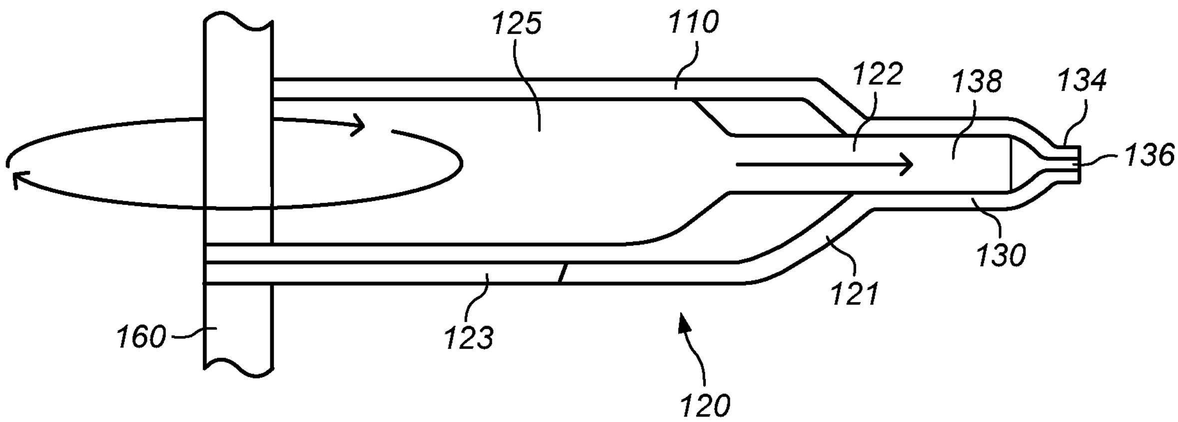
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FIG. 3

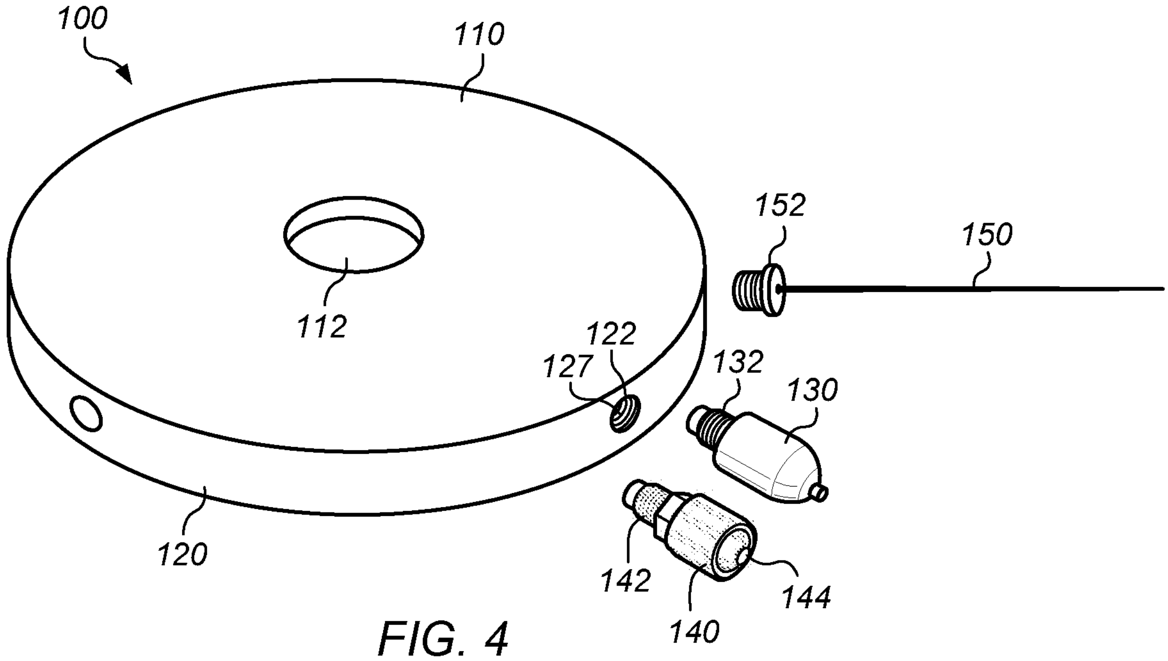
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FIG. 4

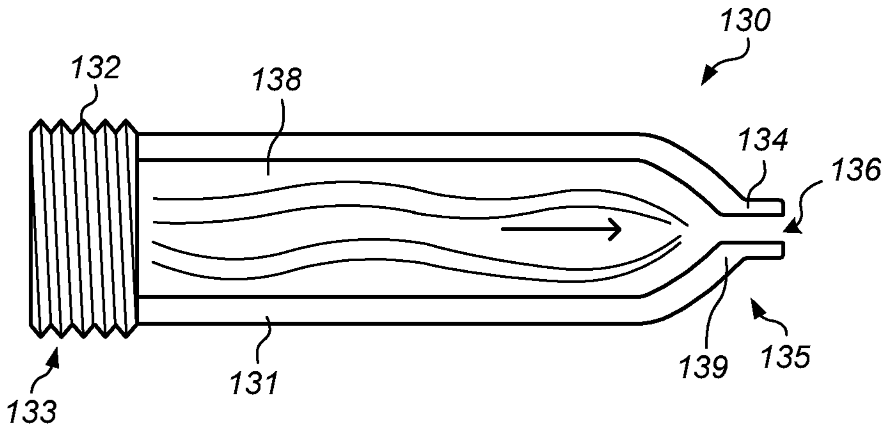
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FIG. 5

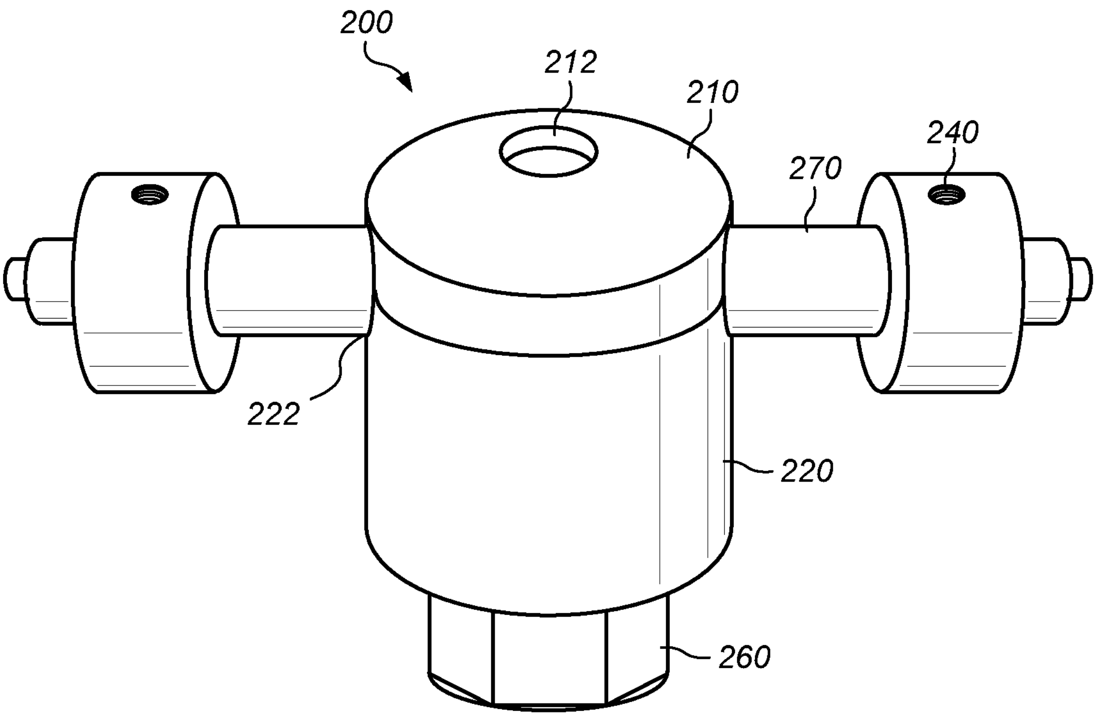

FIG. 6A

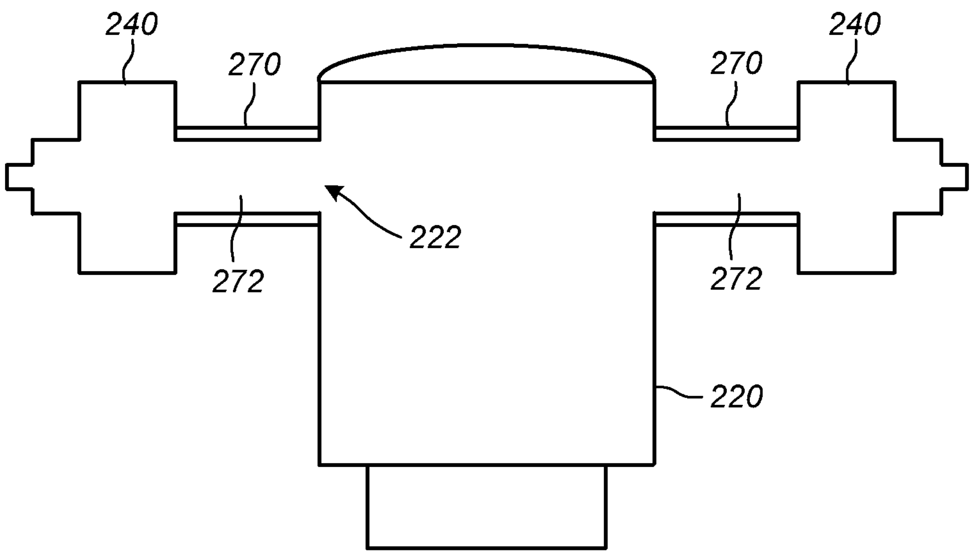

FIG. 6B

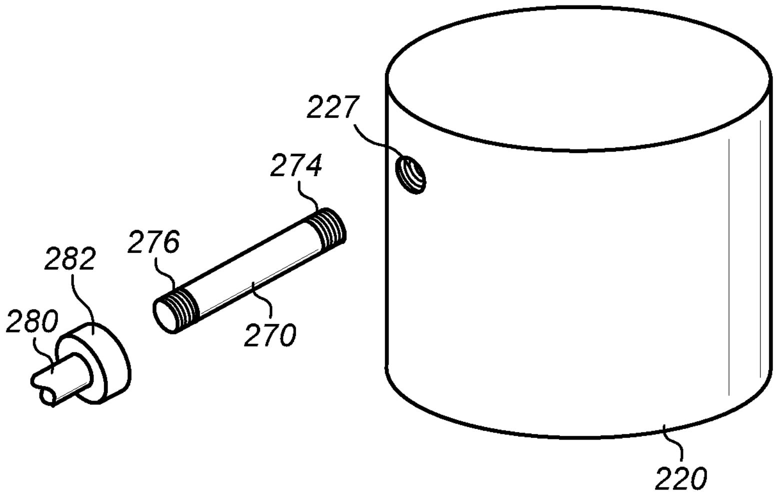

FIG. 7

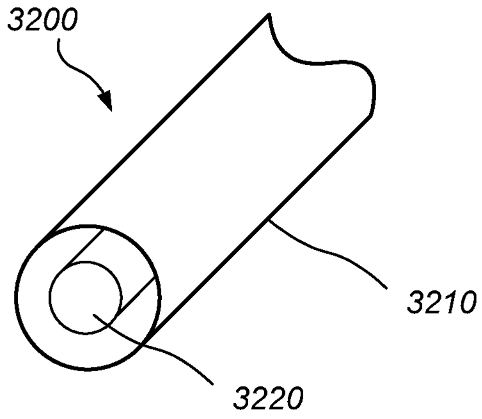

FIG. 8

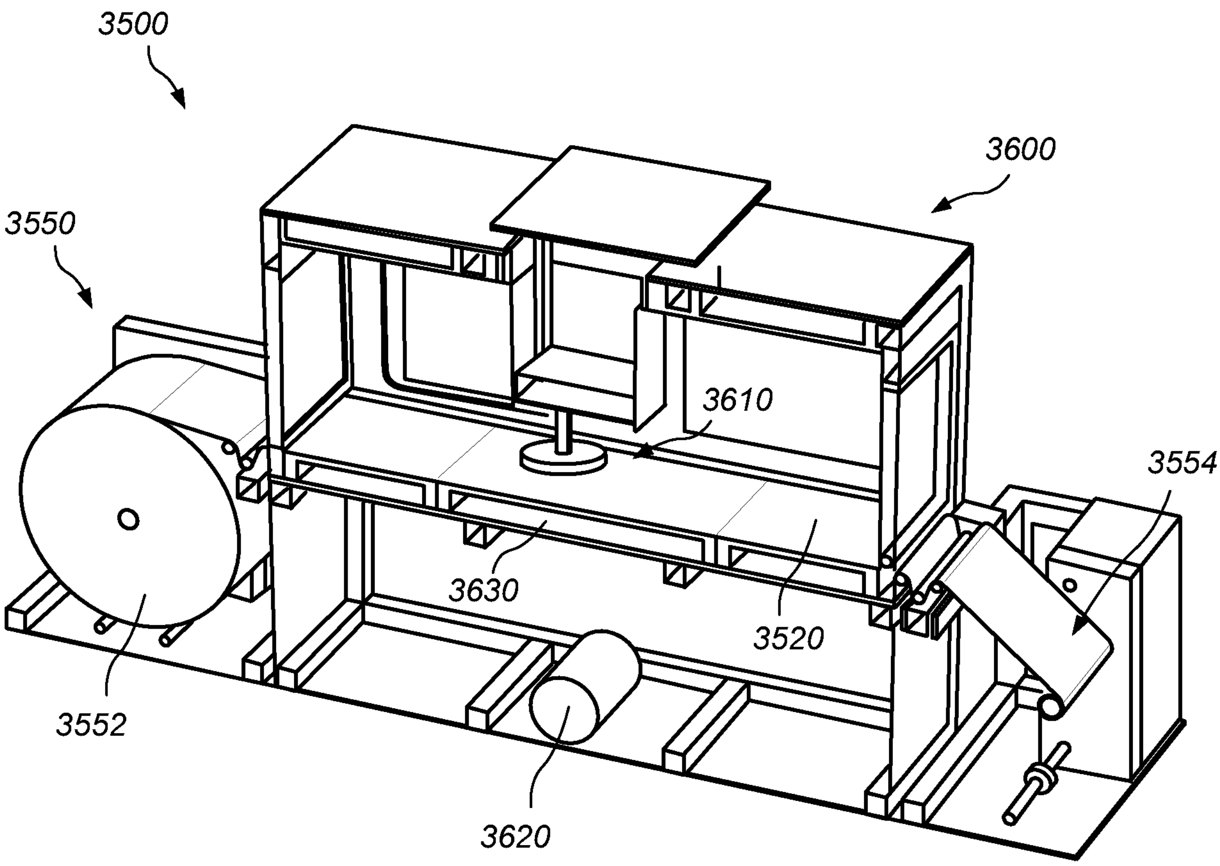

FIG. 9

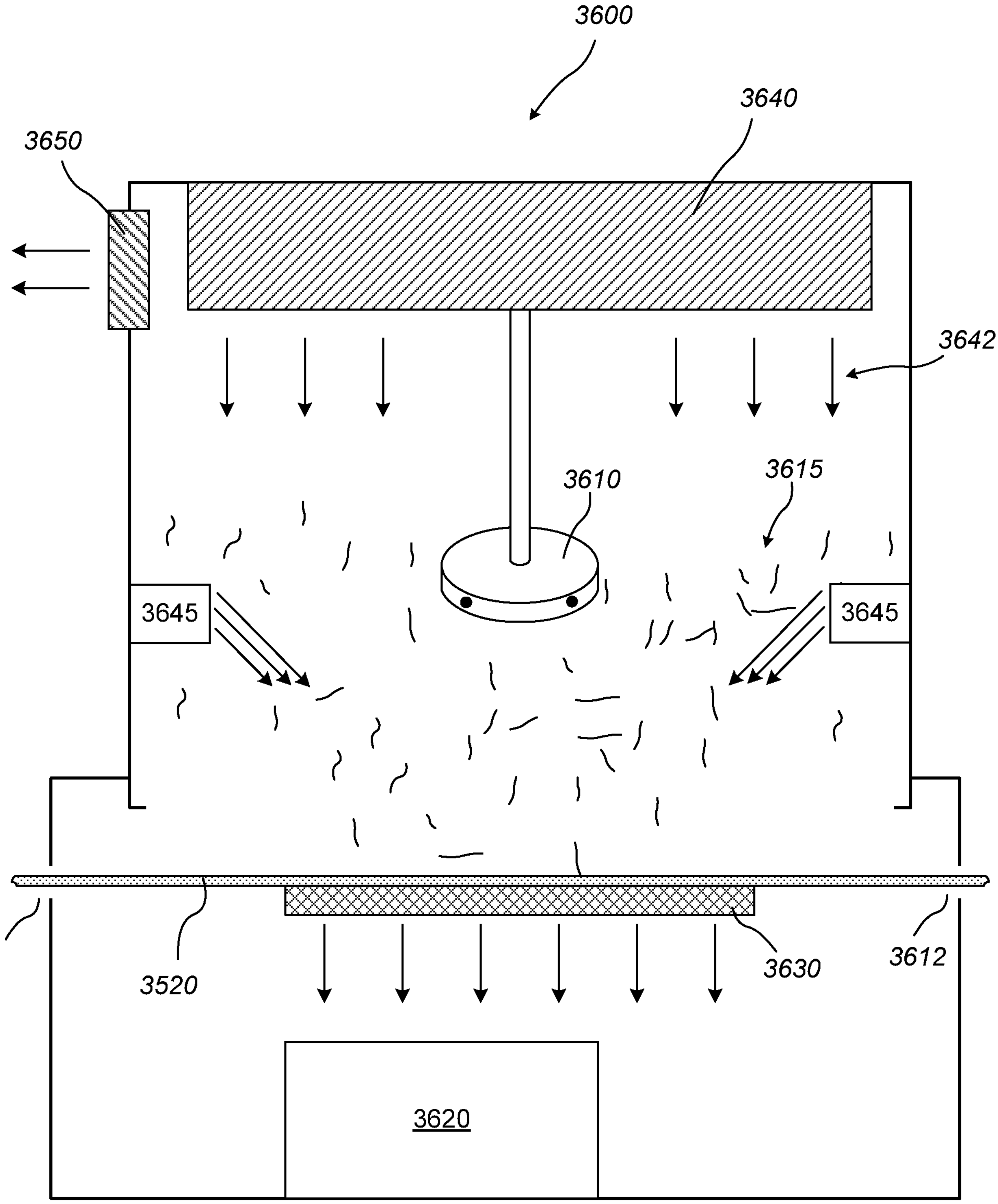

FIG. 10

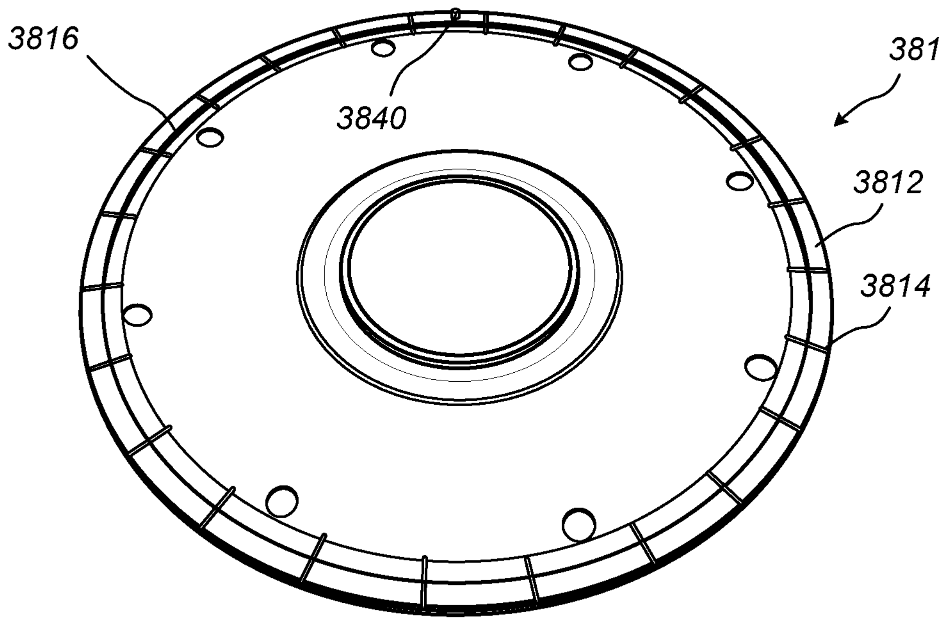

FIG. 11A

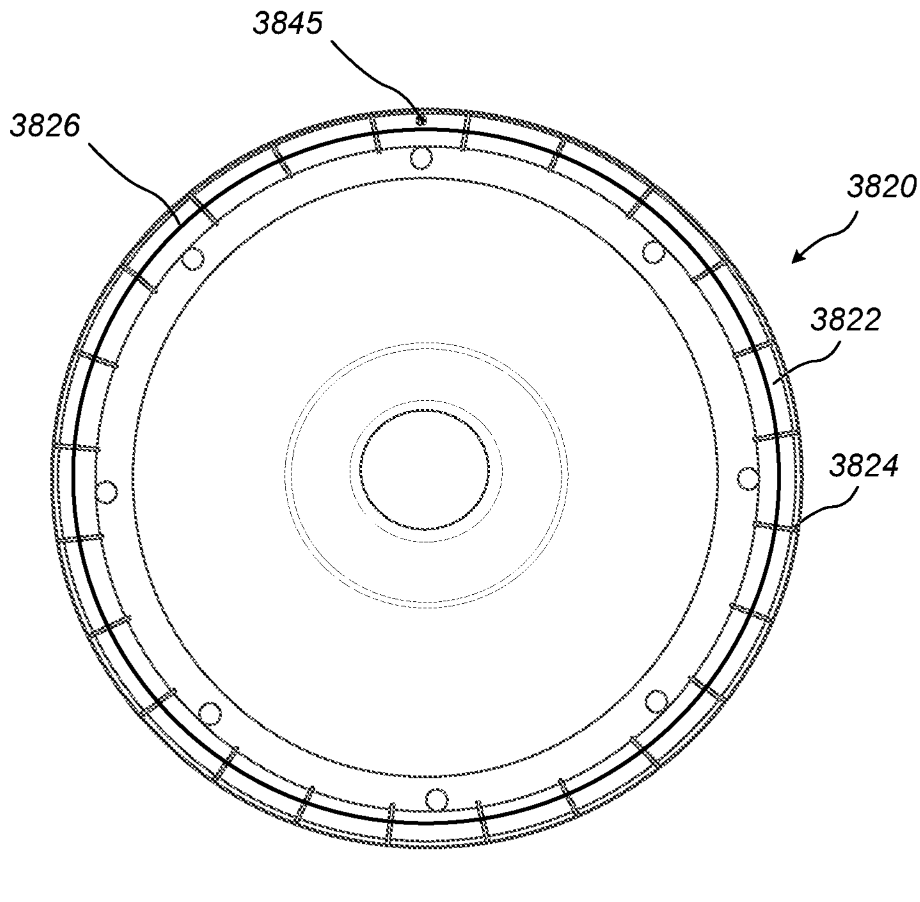

FIG. 11B

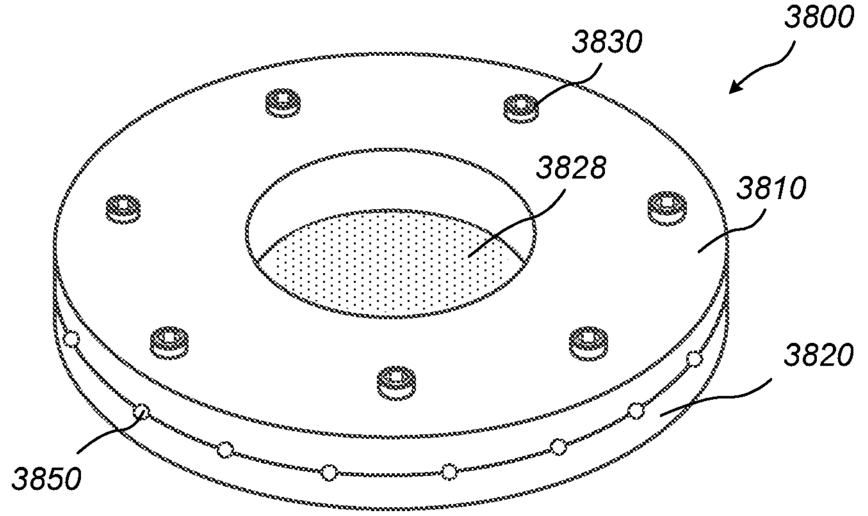

FIG. 11C

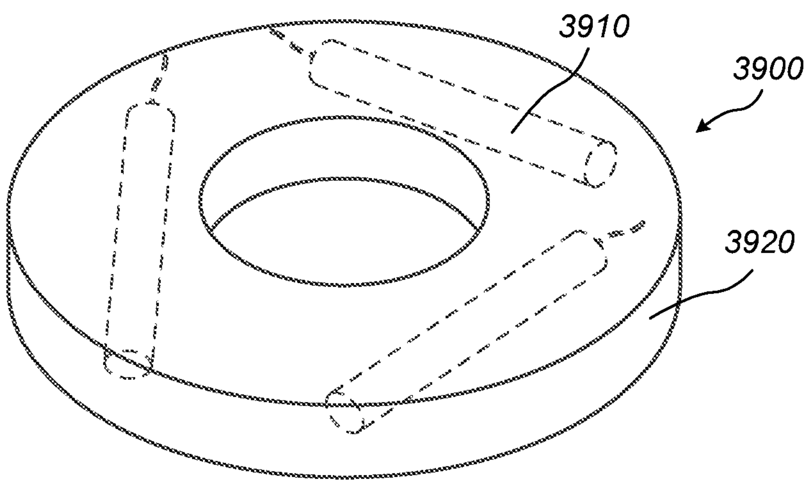

FIG. 12

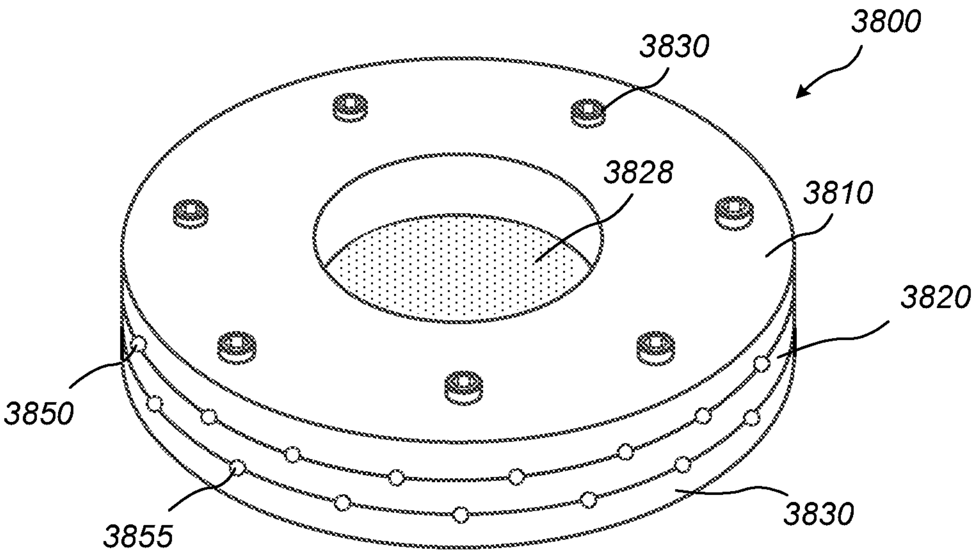

FIG. 11D

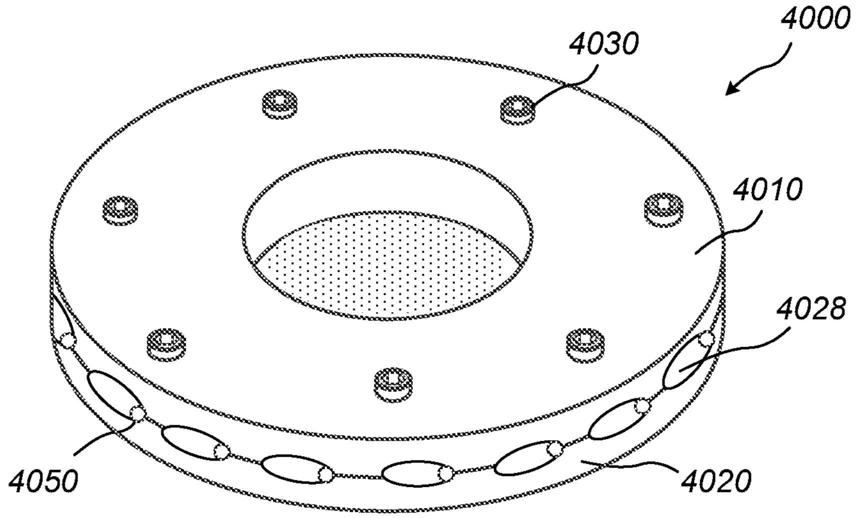

FIG. 13

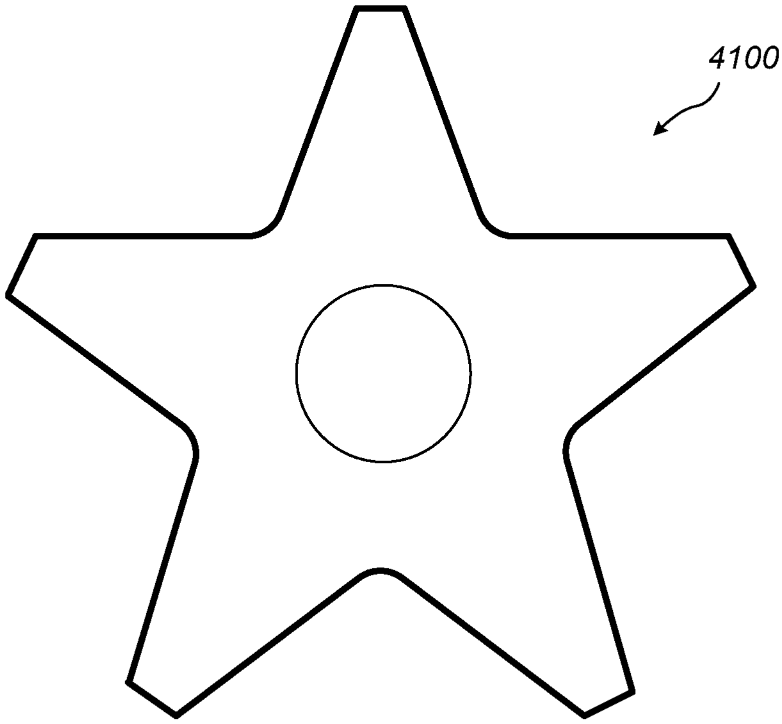

FIG. 14A

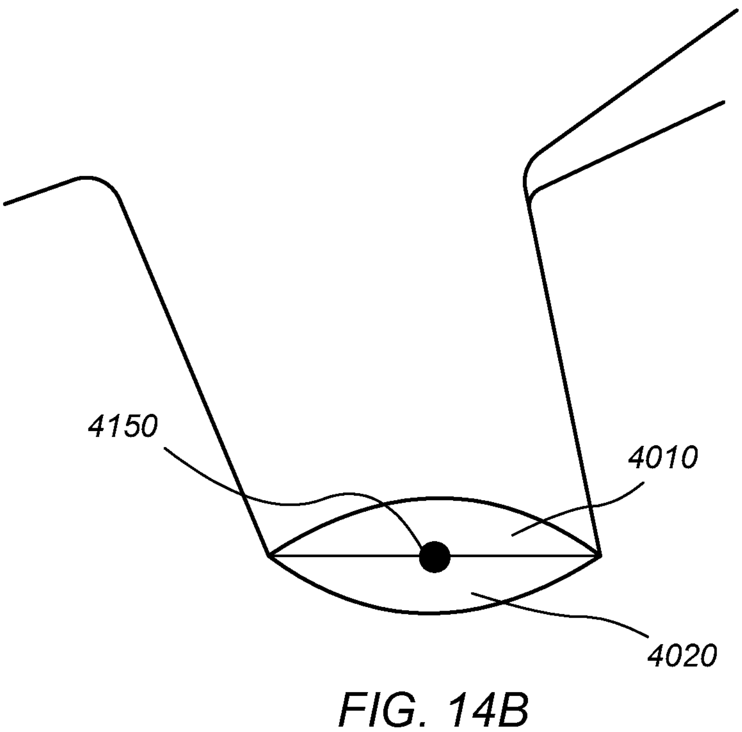

FIG. 14B

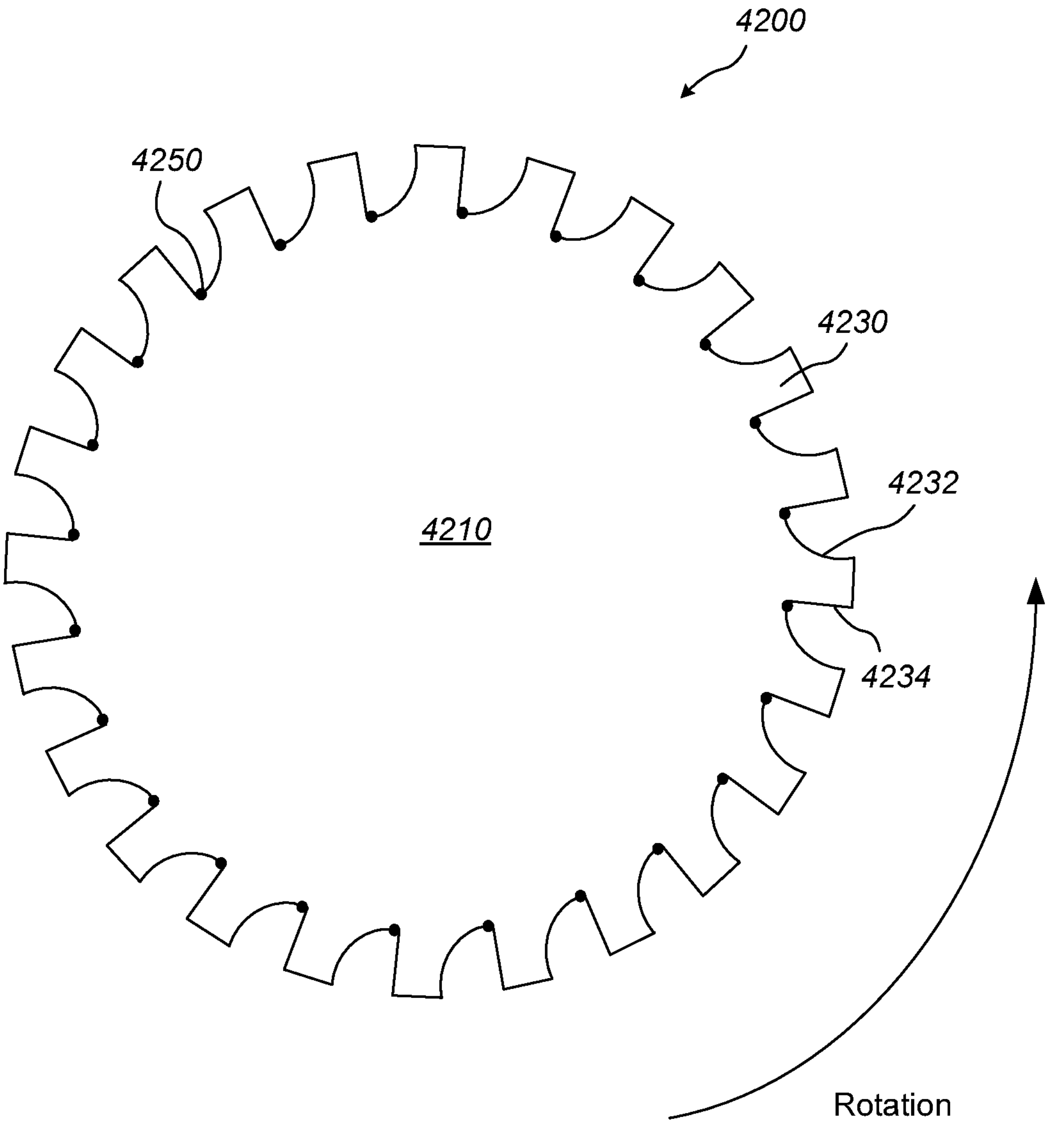

FIG. 15