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(54) **MAGNETO-CALORIC REGENERATOR SYSTEM AND METHOD**

(75) Inventors: **Jayeshkumar Jayanarayan Barve**, Bangalore (IN); **Chandrasekhar Samiappan**, Bangalore (IN); **Sudhakar Eddula Reddy**, Bangalore (IN); **Francis Johnson**, Clifton Park, NY (US); **Atanu Saha**, Bangalore (IN); **Kalaga Murali Krishna**, Bangalore (IN); **Mahesh Chandran**, Bangalore (IN)

(73) Assignee: **GENERAL ELECTRIC COMPANY**, SCHENECTADY, NY (US)

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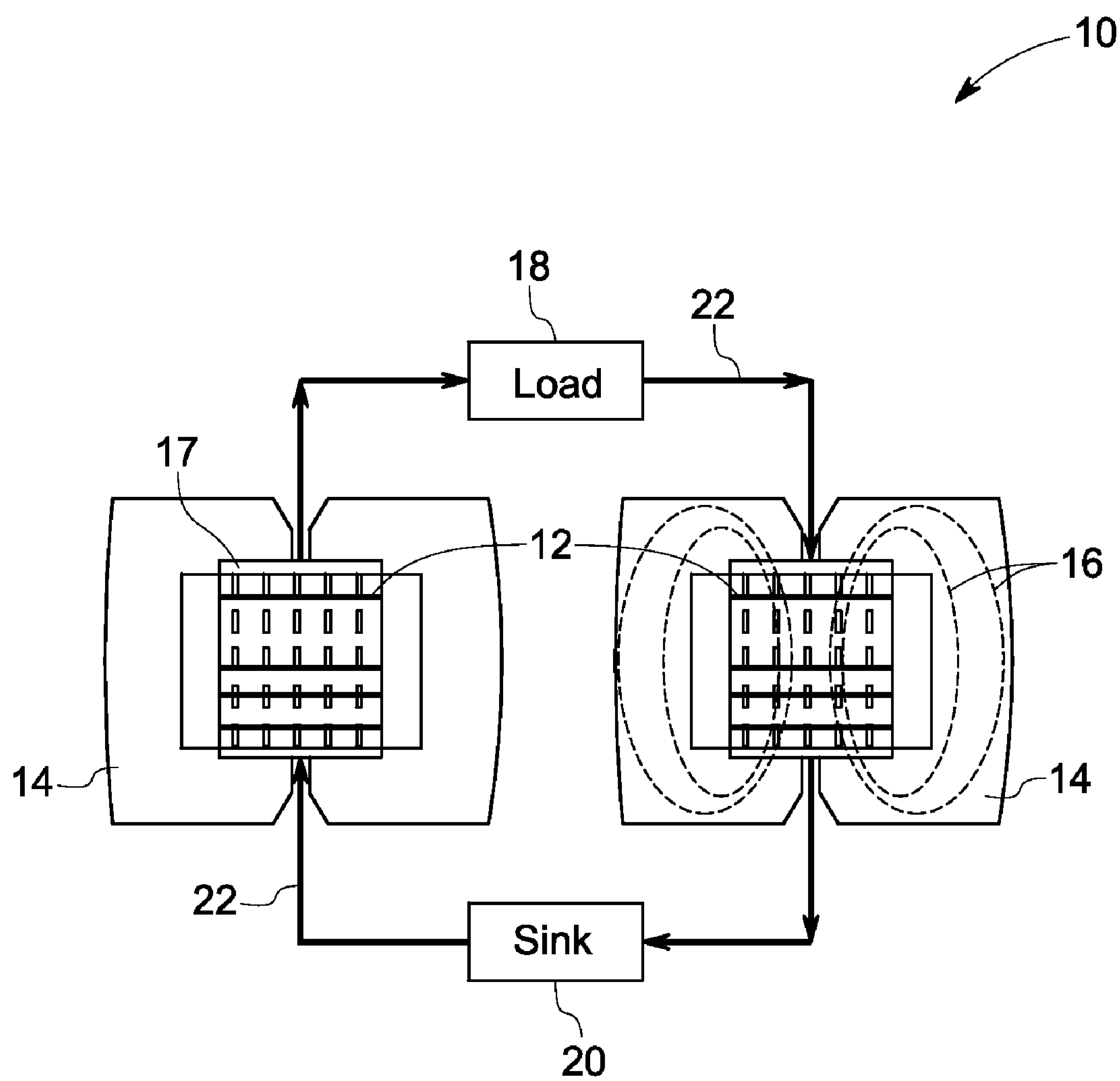
(57) **ABSTRACT**

A regenerator having a thermal diffusivity matrix is presented. The thermal diffusivity matrix includes magneto-caloric material having multiple miniature protrusions intimately packed to form a gap between the protrusions. A fluid path is provided within the gap to facilitate flow of a heat exchange fluid and further provide efficient thermal exchange between the heat exchange fluid and magneto-caloric material. A first layer is disposed on each of the miniature protrusion to physically isolate the heat exchange fluid and magneto-caloric material, wherein the first layer further includes a soft magnetic material configured to simultaneously enhance a permeability and a thermal efficiency of the thermal diffusivity matrix.



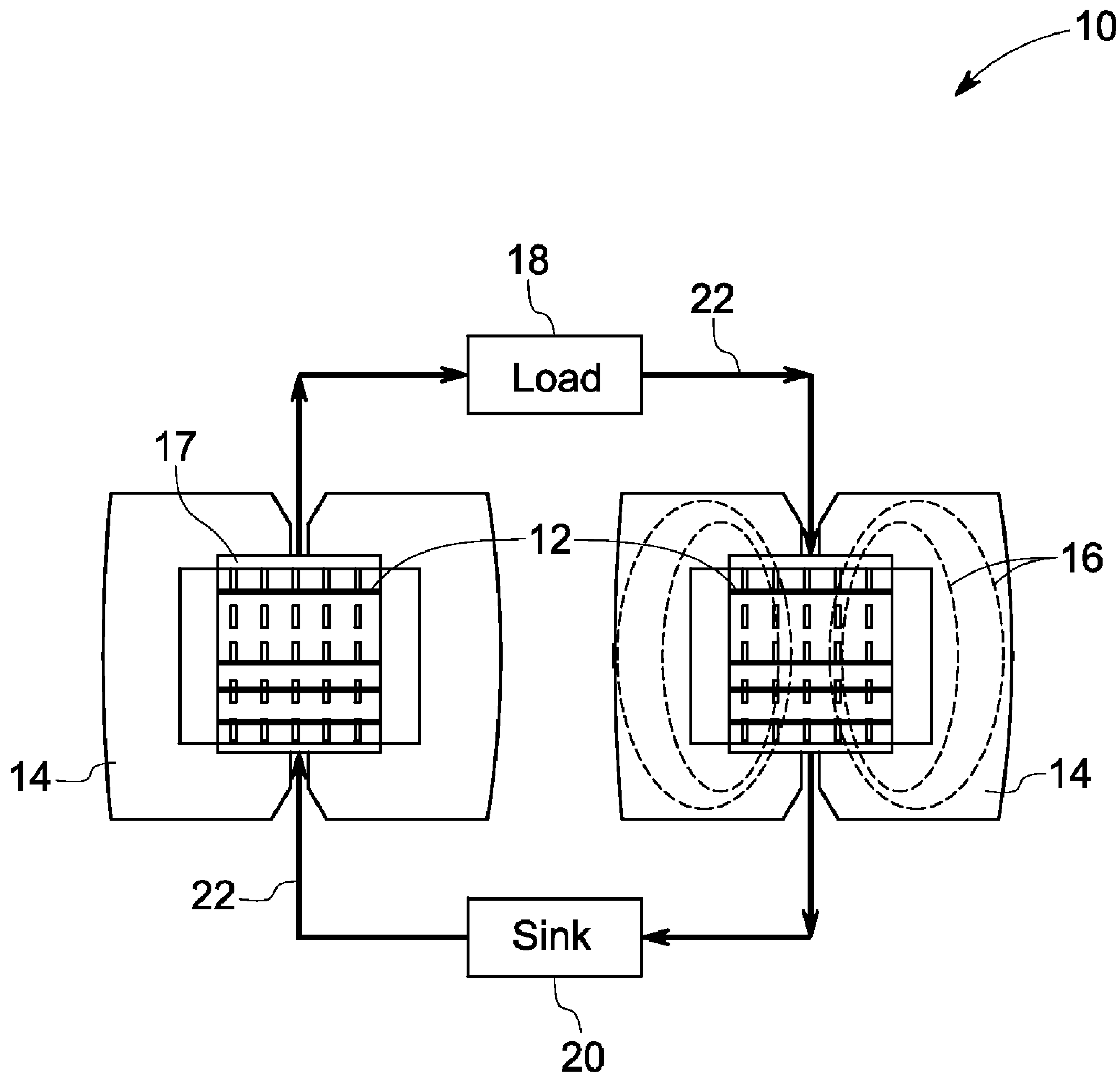


FIG. 1

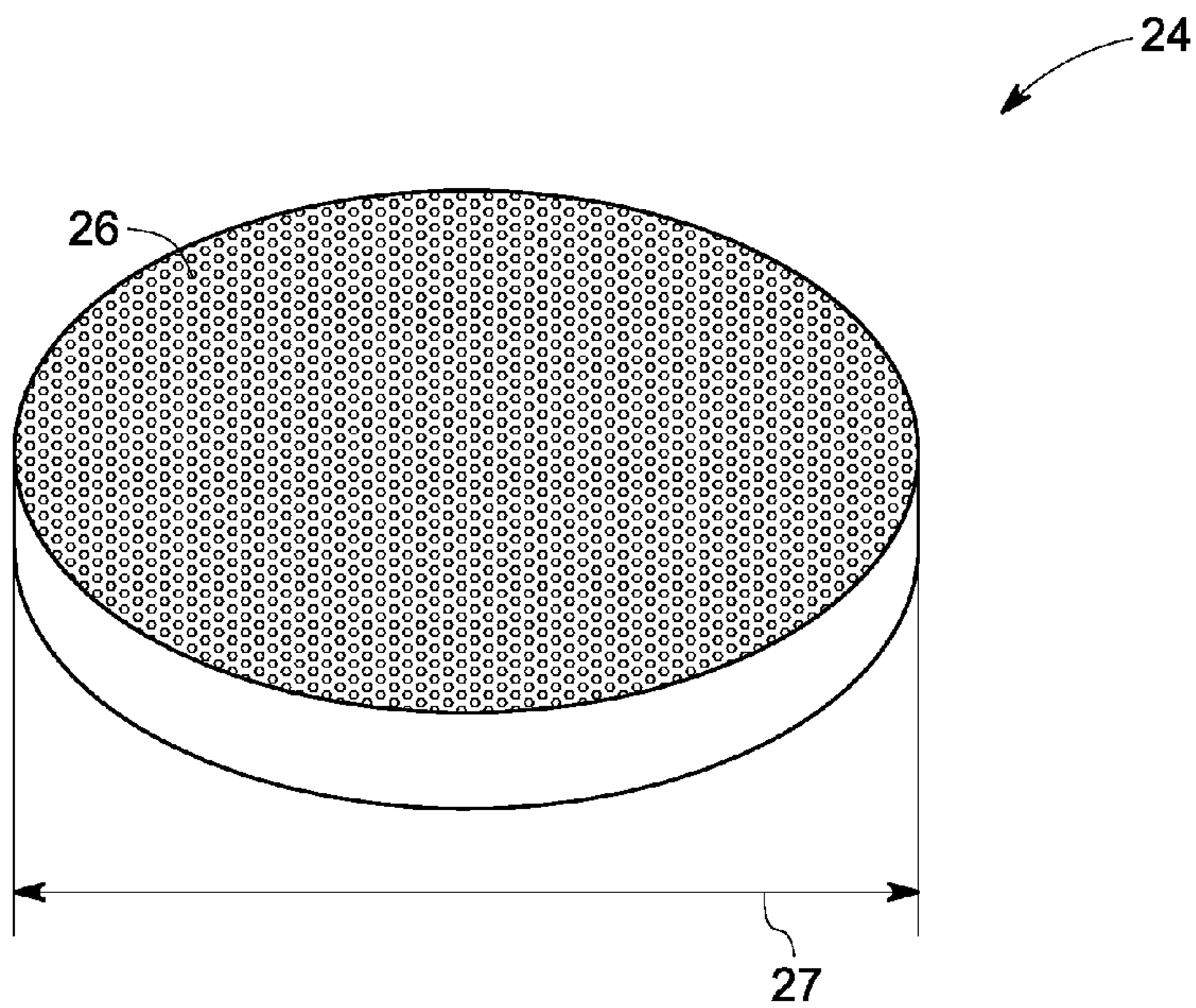


FIG. 2

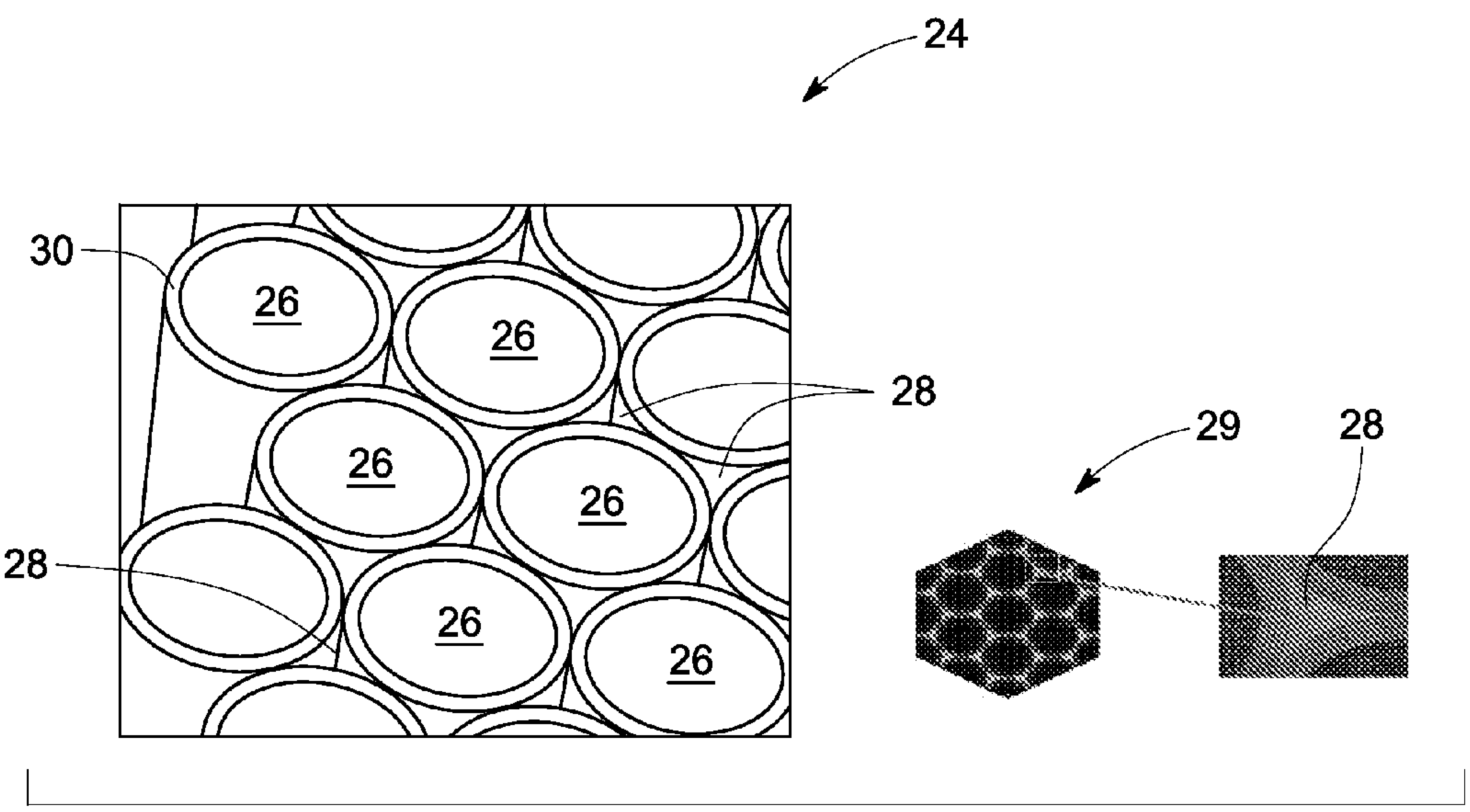


FIG. 3

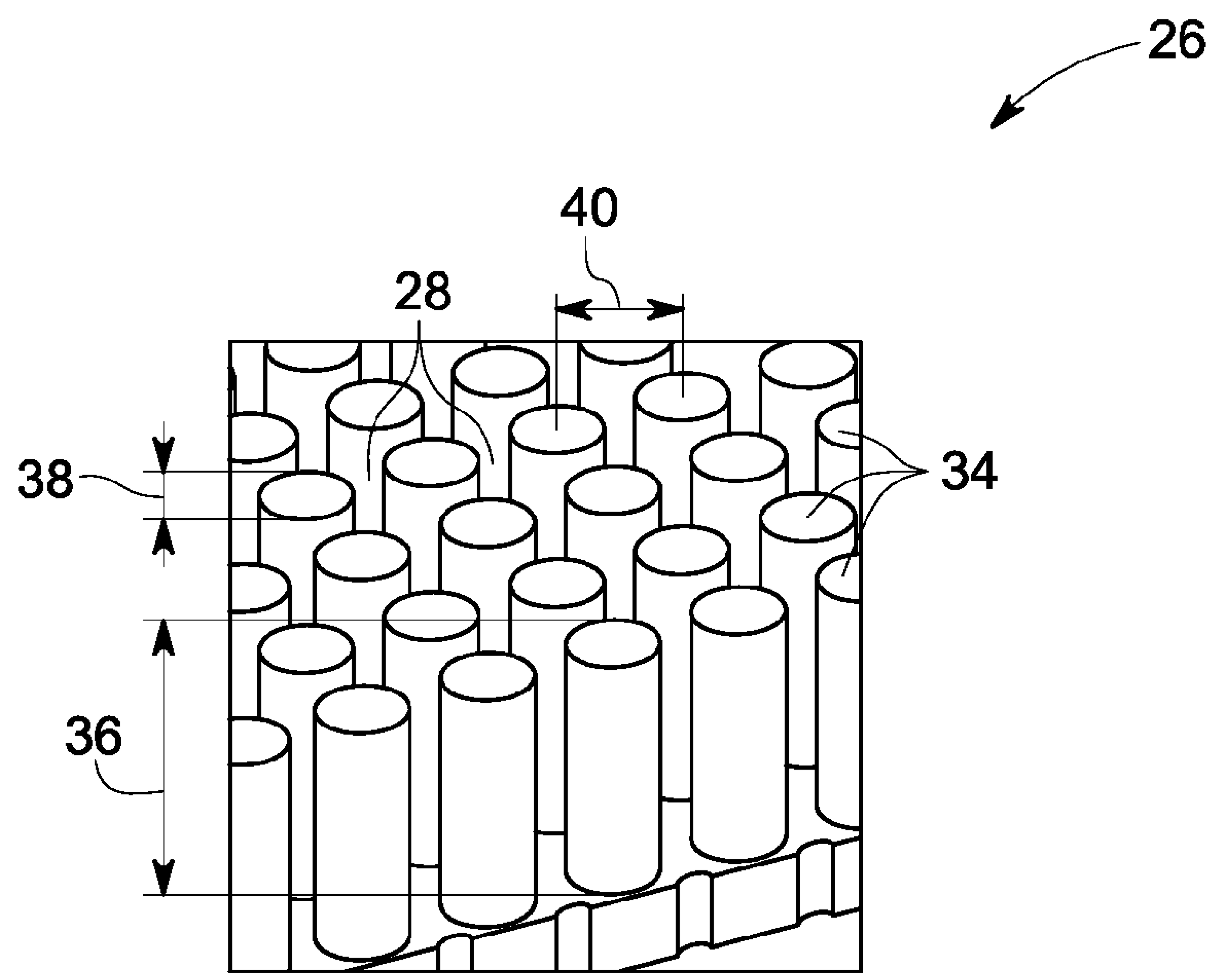


FIG. 4

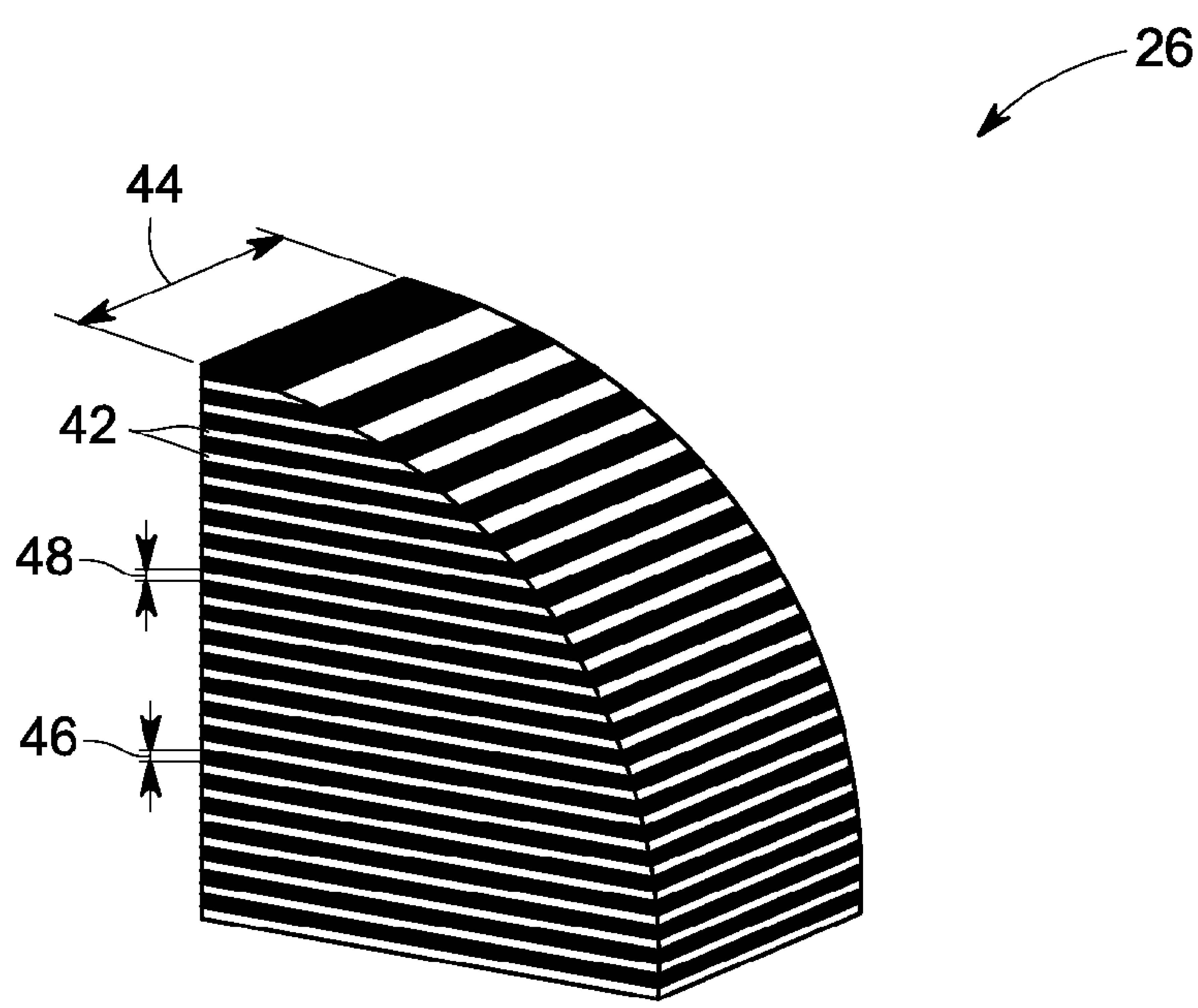


FIG. 5

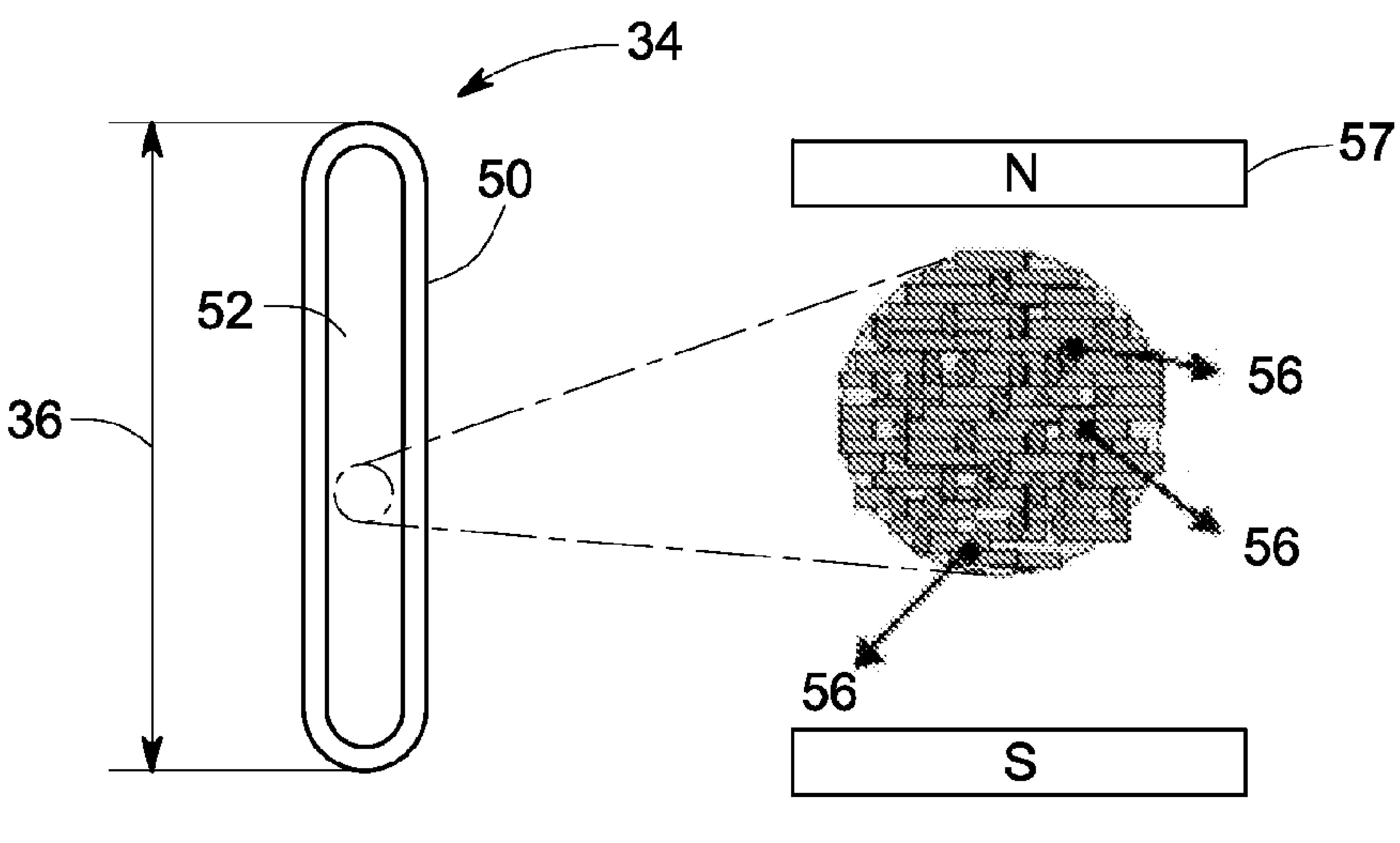

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FIG. 6

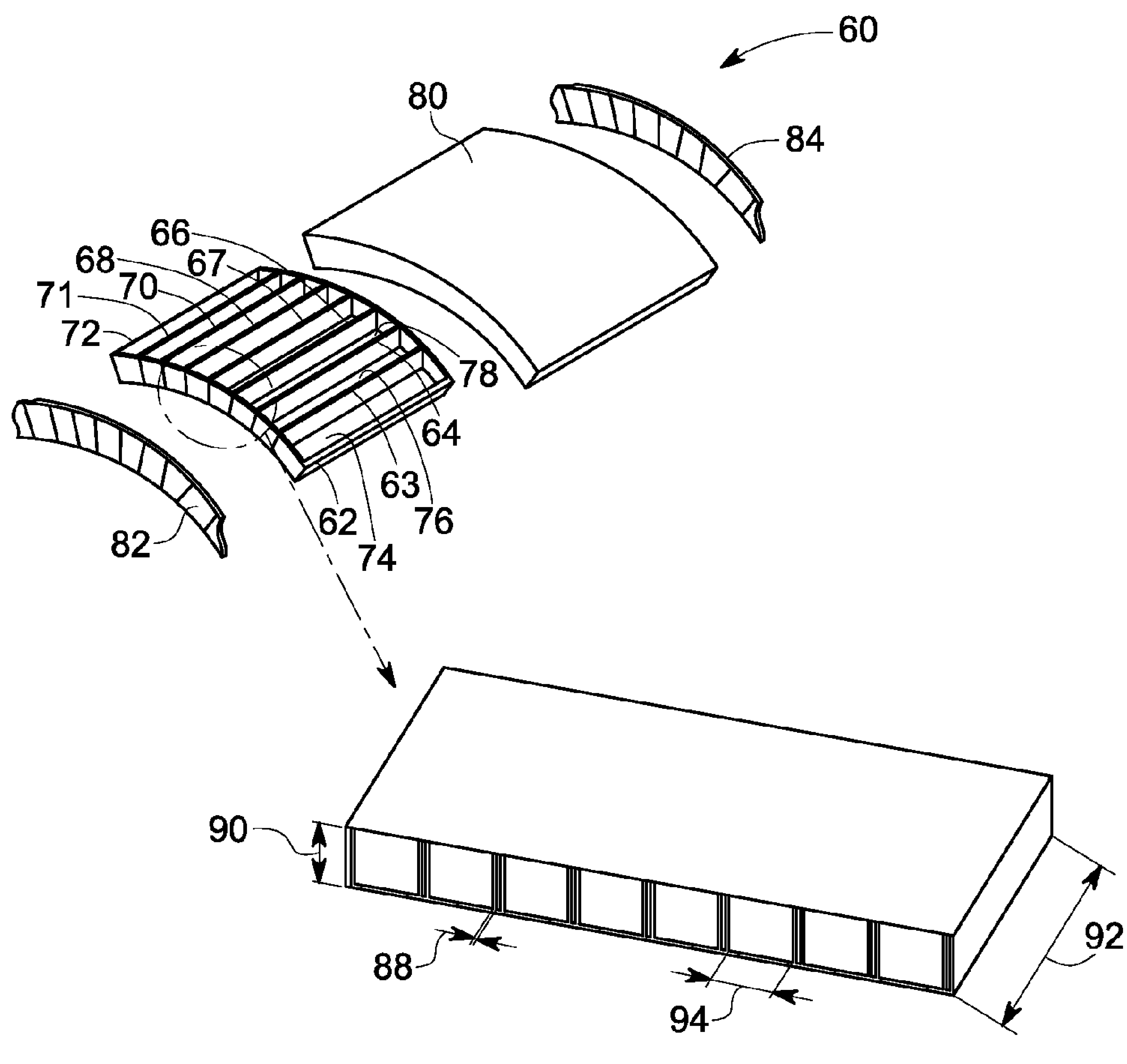
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FIG. 7

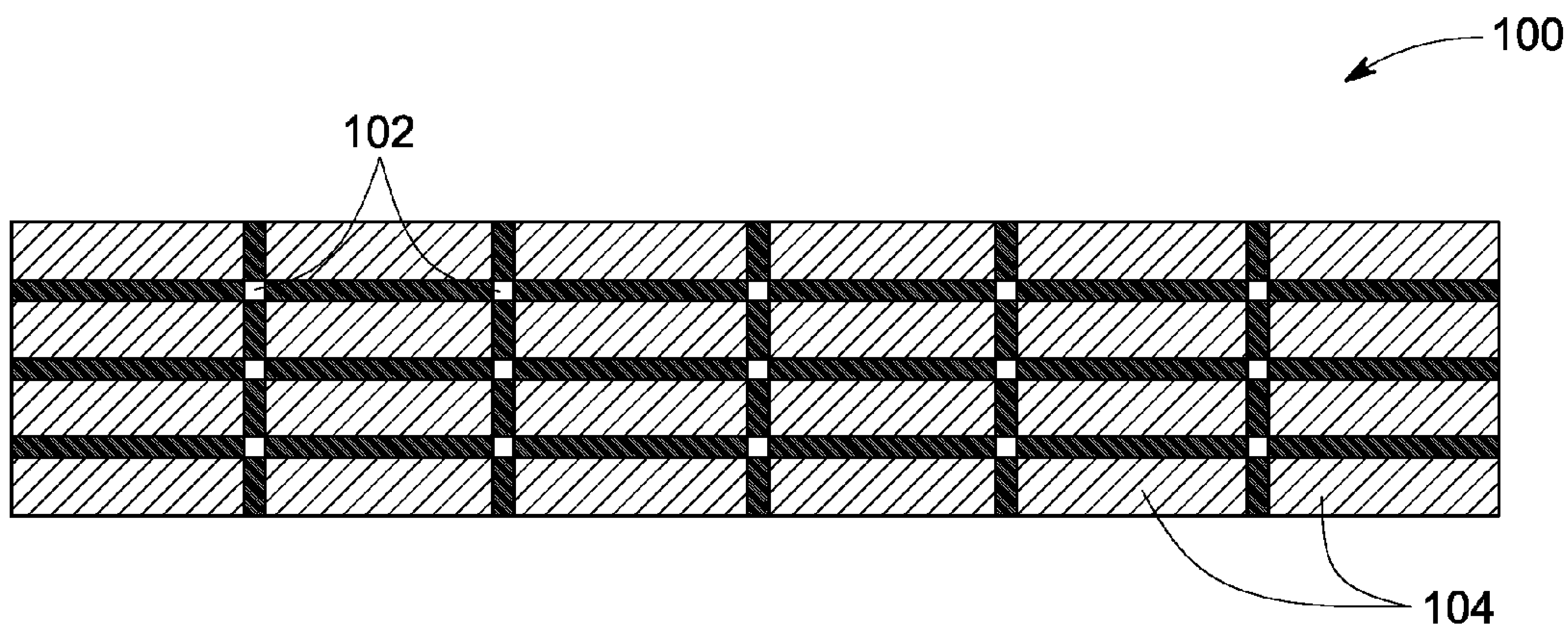

FIG. 8

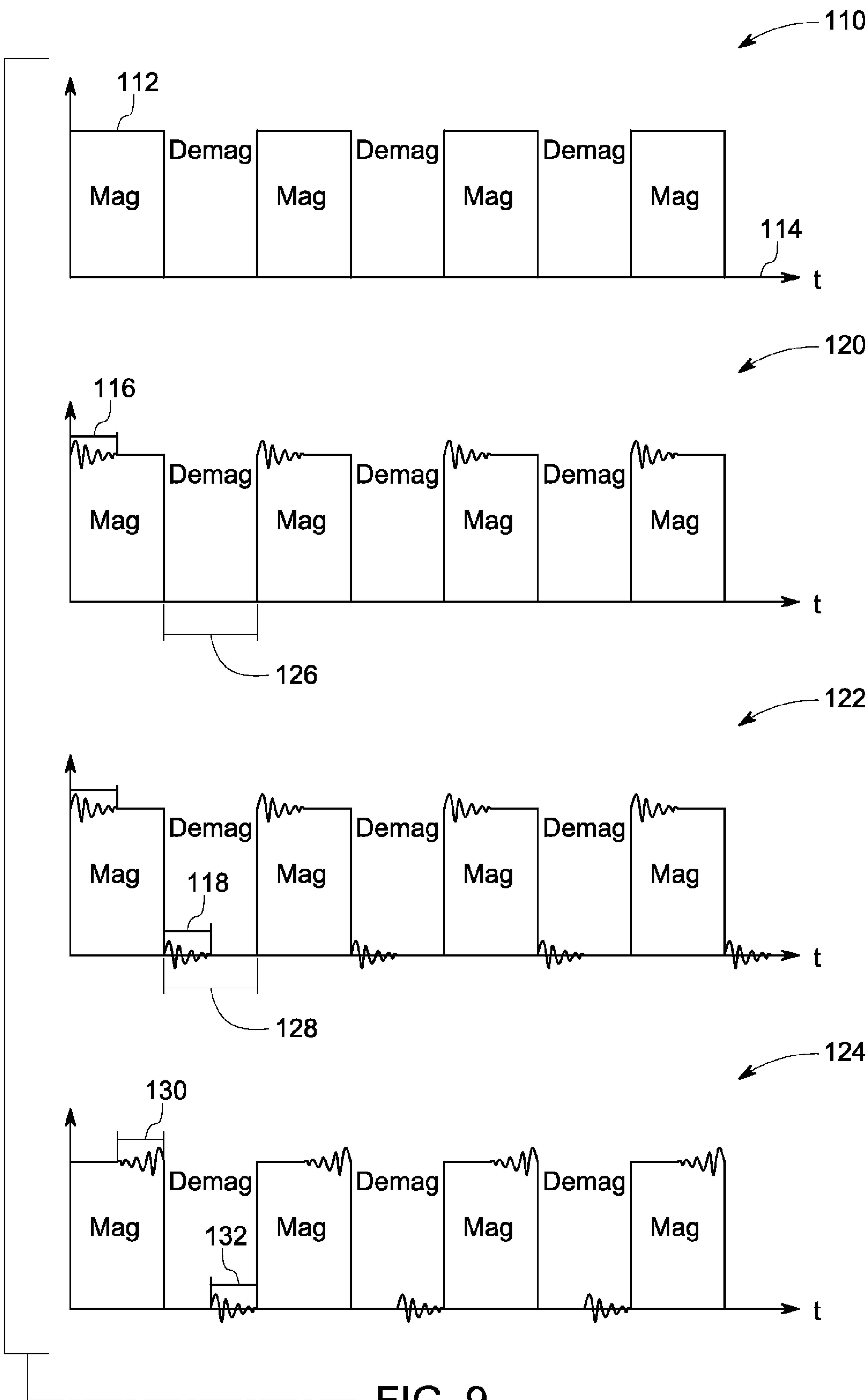
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FIG. 9

MAGNETO-CALORIC REGENERATOR SYSTEM AND METHOD

BACKGROUND

[0001] The subject matter disclosed herein generally relates to magneto-caloric refrigeration and in particular to regenerators in magneto-caloric refrigeration.

[0002] Conventional refrigeration technology has often utilized the adiabatic expansion or the Joule-Thomson effect of a gas. However, such gas compression technology has some drawbacks. First, a Hydro-fluorocarbon (HFC), Hydro-chlorofluorocarbon (HCFC), or chlorofluorocarbon (CFC) gas, a typical refrigerant working material used most commonly in this technology, may pose some level of environmental challenges if not disposed of properly. Additionally, the gas compression technology is a mature technology and extracting additional energy savings out of this technology has proved difficult.

[0003] An alternative refrigeration technique involves a method that takes advantage of entropy change accompanied by a magnetic or magneto-structural phase transition of a magneto-caloric material, referred to as a magnetic phase transformation. In the magnetic refrigeration technique, cooling is effected by using a change in temperature resulting from the entropy change of the magneto-caloric material. More specifically, the magneto-caloric material used in this method alternates between a low magnetic entropy state with a high degree of magnetic orientation created by applying a magnetic field to the magnetic material near its transition temperature (typically near Curie temperature), and a high magnetic entropy state with a low degree of magnetic orientation (randomly oriented state) that is created by removing the magnetic field from the magnetic material. Such transition between high and low magnetic entropy state manifests as transition between low and high lattice entropy state, in turn resulting in warming up or cooling down of the magneto-caloric material when exposed to magnetization and demagnetization. This is called the "magneto-caloric effect." Accordingly, significant research has been directed at leveraging the magneto-caloric effect present within certain magneto-caloric materials to develop a magnetic refrigerator.

[0004] Conventional magneto-caloric based systems require heat exchangers (or regenerators) for heat transfer between the magneto-caloric material and the heat exchange fluid. Magneto-caloric materials include multiple alloys that are typically brittle and have a tendency to become powders due to inherent stress in the material. Furthermore, magneto-caloric materials have low thermal conductivity and hence are less efficient when subjected to transient operating cycle due to cyclic magnetization and demagnetization. Conventional heat exchanger designs use a porous bed structures that have high pressure drop and prone to erosion. Further, several magneto-caloric material when directly exposed to the aqueous (water based) heat exchange fluids reacts to form oxide or hydroxide layer, which in turn lower the efficiency and reliability of the heat exchanger in magneto-caloric refrigeration systems.

[0005] Thus, it would be beneficial to have a thermally efficient heat exchanger to reduce the amount of magneto-caloric material required and hence, reduction in the size and cost of the overall device. Further, lower pressure drop for higher heat exchange fluid flow rates is desirable in magneto-caloric systems.

BRIEF DESCRIPTION

[0006] Briefly, a regenerator having a thermal diffusivity matrix is presented. The thermal diffusivity matrix includes magneto-caloric material having multiple miniature protrusions intimately packed to form a gap between the protrusions. A fluid path is provided within the gap to facilitate flow of a heat exchange fluid and further provide efficient thermal exchange between the heat exchange fluid and magneto-caloric material. A first layer is disposed on each of the miniature protrusion to physically isolate the heat exchange fluid and magneto-caloric material, wherein the first layer further includes a soft magnetic material configured to simultaneously enhance a permeability and a thermal efficiency of the thermal diffusivity matrix.

[0007] In another embodiment, a regenerator having a thermally conducting material is presented. The thermally conducting material defines multiple micro fluidic channels adjacent to each other. A magneto-caloric material is disposed within multiple pockets formed between the micro fluidic channels. A fluid path is defined within said micro fluidic channels. The fluid path facilitates flow of a heat exchange fluid, wherein the heat exchange fluid and magneto-caloric material are in thermal communication and physical isolation.

[0008] A magneto-caloric system having a regenerator, an excitation source, a magnetic core, and a thermal exchange cycle is presenter. The regenerator includes a magnetically aligned cluster of a magneto-caloric material, the cluster having miniature protrusions arranged intimately to form a gap between said each miniature protrusion. A fluid path is defined within the gap and configured to exchange thermal units between a heat exchange fluid and the magneto-caloric material. The excitation source is configured to generate magnetic flux to magnetize and de-magnetize the regenerator cyclically. The magnetic core is configured to channalize magnetic flux throught the regenerator. The thermal exchange cycle is coupled a load, a sink, and the regenerator. The heat exchange fluid facilitates exchange of thermal units between the load and the sink.

[0009] In another embodiment, a magneto-caloric system having a regenerator, a first and second electrical current source, and a heat exchange fluid is presented. The regenerator is made of magneto-caloric material and configured to heat or cool when magnetically excited. The first electrical current source is configured to generate a magnetic field and excite the magneto-caloric material. The second electrical current source is configured to generate a high frequency signal and excite the magneto-caloric material. The heat exchange fluid flows though the regenerator and configured to transfer thermal units between a load and an ambient.

DRAWINGS

[0010] These and other features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

[0011] FIG. **1** illustrates an exemplary cooling device according to an embodiment of the invention;

[0012] FIG. **2** illustrates a regenerator designed according to an aspect of the invention;

[0013] FIG. **3** illustrates a zoomed in view of the miniature protrusions in FIG. **2**;

[0014] FIG. **4** illustrates a perspective view of the miniature protrusions in FIG. **2**;

[0015] FIG. **5** illustrates miniature plate structures according to an embodiment of the invention;

[0016] FIG. **6** illustrates a detailed view of pin structure of FIG. **4**;

[0017] FIG. **7** illustrates a regenerator structure according to an embodiment of the invention;

[0018] FIG. **8** illustrates arrangement of fluid channels and magneto-caloric material; and

[0019] FIG. **9** illustrates magnetizing pulse according to an embodiment of the invention.

DETAILED DESCRIPTION

[0020] Typically, the magnetic-caloric system is based on the active magnetic regenerative (AMR) cycle. The AMR cycle implements magneto-caloric materials based heat exchangers often referred as regenerators for heat transfer between magneto-caloric material and a heat exchange fluid. Multiple layers of magneto-caloric material with different Curie temperature are used to achieve the temperature span. Regenerators would also include insulating layers between the stages to help maintain the thermal losses and hence the temperature gradient across regenerators. Embodiments disclosed herein, describes various aspects to design and fabrication of regenerators and magneto-caloric systems.

[0021] Referring now to the drawings, FIG. **1** illustrates an exemplary magneto-caloric refrigeration system **10** that is configured to provide cooling using the magneto-caloric effect. The system **10** includes a regenerator **17** having multiple magneto-caloric elements coupled thermally (represented by reference numeral **12**). The magneto-caloric elements include magnetically aligned clusters of magneto-caloric material. The cluster having the miniature structures is arranged intimately such that gaps are formed between the miniature structures. A magnet assembly **14** is disposed around the regenerator **17**. The magnet assembly, for example, may include a permanent magnet or an electromagnet. The magnet assembly is configured to generate magnetic flux that magnetizes or demagnetizes the plurality of magneto-caloric elements **12** within the regenerator cyclically. A load **18** and a sink **20** are coupled through a fluid circuit **22**. A fluid path formed within the gap is coupled to the fluid circuit **22**. A heat exchange fluid is configured to flow through the fluid path and fluid circuit **22**.

[0022] In operation, the system **10** is configured to sequentially regulate the temperature of the plurality of magneto-caloric elements **12** within the regenerator **17**, for maximizing the magneto-caloric effect for each of the plurality of magneto-caloric elements **12** when subjected to a magnetic regenerative refrigeration cycle. In particular, the plurality of magneto-caloric elements may be heated or cooled through isentropic magnetization, or isentropic demagnetization (via magnetic field **16**) and through transfer of heat using a fluid medium. The magneto-caloric elements **12** are excited by a magnetic field **16** generated by the magnet assembly **14**. Such excitation results in heating or cooling of the magneto-caloric elements **12**. In this embodiment, the system **10** includes a load **18** and a sink **20** thermally coupled to the magneto-caloric elements **12** in the regenerator **17**. The load **18** and the sink **20** include the fluid medium for transferring the heat between the magneto-caloric elements **12** and the environment. The fluid medium, for example, a heat exchange fluid, is configured to exchange thermal units with the magneto-caloric material. The magneto-caloric elements **12** also are designed for efficient exchange of thermal units. The heat exchange fluid **22** facilitates exchange of thermal units between the load **18** and the sink **20** that in turn heat or cool the load **18**.

[0023] Typically, heat exchange fluids in the magneto-caloric system have low freezing point (also the lowest fluid temperature in the AMR cycle,) enhanced thermal properties, non-toxic, and non-flammable. Thermal properties of the heat exchange fluid such as thermal conductivity, specific heat capacity, density and viscosity affect the thermal efficiency of the regenerator. Typically, any heat exchange fluid should have high specific heat capacity, high density, high thermal conductivity and low viscosity. Such properties improve the heat transfer coefficients for convection heat transfer in the regenerator and reduce pumping losses. High specific heat capacity would ensure more heat being transferred between the magneto-caloric materials and the heat exchange fluid resulting in higher regenerator efficiency. Non-limiting examples of heat exchange fluids include Paratherm LR®, Multi-therm PG-1®, Syltherm® and Dowfrost®. Further, non-limiting examples of water based heat exchange fluids include Dynalene HC-30® and Dowcal®.

[0024] Reduction in thermal efficiency will require increased mass of magneto-caloric material and hence increasing the overall size & weight of the magnet assembly. Certain embodiments disclosed herein implement efficient regenerator design that help optimize various system level parameters such as cooling temperature range, cooling rate, load, size, weight, cost and overall thermal efficiency.

[0025] Chemical properties of magneto-caloric materials influence the design of regenerators. Rare earth based magneto-caloric materials particularly may not be chemically compatible with the aqueous based heat exchange fluid. Such magneto-caloric materials react with aqueous based heat exchange fluids to form metal hydroxides and oxides on the surface. Such hydroxides and oxides lead to creation of undesirable layer of oxide and hydroxides on the surface of magneto-caloric material in the regenerator. Since hydroxide and oxide have low thermal conductivities, the decreases heat transfer capability from heat exchange fluid to magneto-caloric material and vice versa, decreasing the thermal efficiency of the regenerator. Chemical compatibility of the magneto-caloric materials may be improved by disposing a protective layer that is thermally conducting and chemically inert. Such protective layer act as barrier between the magneto-caloric material and the heat exchange fluid and protect the regenerator system from degradation. In certain embodiments of the invention, physical isolation between the magneto-caloric material and the heat exchange fluid are disclosed to enhance the chemical properties of magneto-caloric materials.

[0026] Magnetic flux lines pass directly through regenerator that is part of the magnet assembly. Magneto-caloric materials generally have lower magnetic permeability as compared to soft iron, particularly around operating temperature ranges. Accordingly, high magnetic field is required for generation of magneto-caloric effect. Further, poor permeability of magneto-caloric materials demands large size magnets to produce high intensity magnetic field. In one embodiment, regenerator implements a design to have high permeability (or low demagnetization effects) via optimized regenerator structure. Further, a high aspect ratio is designed to orient the magnetic flux resulting in higher efficiency.

[0027] FIGS. **2-5** illustrated a regenerator designed according to an aspect of the invention. The regenerator **24** includes a thermal diffusivity matrix having a plurality of miniature protrusions **26** optimized to enhance magnetic permeability. The miniature protrusions are made of magneto-caloric material and intimately packed to form a gap (**28** as referenced in FIG. **3**) between the protrusions. The magnetic field (**16** as referenced in FIG. **1**) is applied to excite the magneto-caloric material that in turn heats or cools the magneto-caloric material. A fluid path is defined within the gap to facilitate flow of a heat exchange fluid (not shown) and efficient thermal exchange between the heat exchange fluid and magneto-caloric material. The miniature protrusions **26** may include at least one of a cylindrical or a pin structure as will be described in detail at FIG. **4**. In another embodiment, the miniature protrusions **26** may include a plate structure as will be discussed in detail at FIG. **5**. Still referring to FIG. **2**, the circular structure illustrated herein is exemplary. Alternate structures such as an elliptical or polygonal structure may be implemented for regenerator design.

[0028] FIG. **3** illustrates a zoomed in view of the miniature protrusions of FIG. **2**. A fluid path **28** is defined through the miniature protrusions **26** and configured for efficient exchange of thermal units between the heat exchange fluid (not shown) and the magneto-caloric material. In one embodiment, a first layer **30** that is thermally conductive and made of soft magnetic material (for example, nickel, or chromium) is disposed around the miniature protrusions **26**.

[0029] The first layer is configured to physically isolate the heat exchange fluid and magneto-caloric material. Non-limiting examples of the first layer include materials such as Ni, Ag, Cu, and carbon/graphite. Several coating techniques, both vacuum and non-vacuum based, may be adopted. Vacuum based techniques such sputtering, non-vacuum techniques such as electroplating, or polymer based brush painting followed by curing may be used to dispose the first layer the magneto-caloric material. It may be noted that, such thermally conductive and soft magnetic layer simultaneously enhances a permeability and a thermal efficiency of the regenerator. In another embodiment, the first layer includes a carbon material that is effective corrosion resistant and to prevented degradation of magneto-caloric material in the regenerator.

[0030] Still referring to FIG. **3**, heat exchange fluid is configured to flow through the fluid path **28** and heat or cool (by way of thermal interaction with the magneto-caloric material) the load coupled to the sink. In another embodiment, the pins **34** are arranged in a cluster forming a honeycomb structure as referenced by the numeral **29**.

[0031] FIG. **4** illustrates a perspective view of the miniature protrusions in FIG. **2**. The miniature protrusions include cylindrical or pin structure **34** wherein the longer edge **36** is aligned substantially parallel to the magnetic field. To maximize magnetic permeability, the aspect ratio of the pins (defined as the ratio of the pin length **36** to the pin cross section area) is typically configured to be greater than one. In an exemplary embodiment, the miniature protrusion comprises a high aspect ratio such that the height of each miniature protrusion (**36**) is at least more than 10 times the cross-section area of each said miniature protrusion. In one embodiment, the aspect ratio of up to 25 is designed for enhanced permeability. The high aspect ratio, with longer length (**36**) of the pin aligned in the direction of magnetic field reduces the demagnetization factor and hence improves permeability, which in turn increases the magnetic flux linkage within the magneto-caloric material. Further, the overall pin structure volume is configured to be at least twice the volume of the magneto-caloric material for maximum heat transfer efficiency. In another embodiment, the pins **34** are arranged in a cluster forming a honeycomb structure as illustrated by the reference numeral **29**.

[0032] In an exemplary embodiment, a regenerator disc of about 50 mm to about 100 mm in diameter (Reference numeral **27** as referenced in FIG. **2**) is implemented. The pin height (**36**) of about 5 mm to about 10 mm and pin diameter (**38**) of about 0.5 mm to about 1 mm is implemented. As discussed above the aspect ratio is configured for about 25 (the ratio between pin height (**36**) and pin cross-sectional area.) The pitch (**40**) between pins is designed for about 0.1 d to about 5 d wherein d is the diameter (**38**) of the pin.

[0033] Thermally conducting and chemically inert layer **30** (as referenced in FIG. **3**) having a thickness of about 5 micron to about 500 micron may be disposed around the pins for enhanced chemical and magnetic properties. The circular structure of pins as illustrated herein is exemplary. A pin having an elliptical or polygonal cross-section or any combination thereof may be utilized. Further, the pins illustrated herein are solid. However, a hollow pin structure of the similar shape and dimension may be implemented.

[0034] FIG. **5** illustrates another embodiment of miniature protrusions in FIG. **2** implementing a cluster of miniature plates. In the illustrated embodiment, the miniature protrusions include miniature plate structures **42**. In an exemplary embodiment, the overall plate structure volume is configured to be at least twice the volume of the magneto-caloric material for maximum heat transfer efficiency. The plate structure includes multiple discs/plates **42** wherein the dimensions of each disc include disc height (**44**) of about 1 mm to about 10 mm, disc thickness (**46**) of about 0.1 mm to about 3 mm, and a distance between discs (**48**) of about 0.1 t to about 5 t wherein t is the thickness of the disc. Further, thermally conducting and chemically inert layer of about 5 micron to about 500 micron may be implemented around each disc for enhanced thermal and chemical properties of the regenerator.

[0035] In an alternate embodiment, the disc **42** includes a corrugated plates structure. Further the discs may include dimples or groves or any combination thereof. Discs in the illustrated embodiment are solid. However, hollow discs of the similar shape and dimension may be implemented. In one embodiment, the discs are substantially parallel to each other. In another embodiment, the discs may include non-parallel arrangement of discs.

[0036] FIG. **6** illustrates a detailed view of pin structure in FIG. **4**. In one embodiment, the pin **34** includes a first layer **50** around the magneto-caloric material **52**. The first layer **50** is configured to be thermally conducting and provide physical and chemical isolation between the magneto-caloric material **52** and heat exchange fluid that flows around the pin **34**. Such isolation layer **50** enhances chemical aspects of the magneto-caloric material and prevents reaction with aqueous based and other reactive heat exchange fluids. Further, layer **50** prevents formation of hydroxides and other thermally insulating layers on magneto-caloric material **52** when exposed to external environment. The longer side (**36**) of the pin **34** is aligned along the magnetic field applied around the regenerator. Reference numeral **54** illustrates a further detailed view of the grains **56** within the magneto-caloric material **52**. In an exemplary embodiment, an external magnetic field (of the order of 2.1 kilogauss magnetic intensity) is applied via an external magnetic source **57** during the fabrication of pins **34**, to magnetically align the spin within one or more magnetic domains of the grains **56** towards the orientation of the magnetic flux **16** applied to the regenerator as referenced in FIG. **1**

[0037] FIG. **7** illustrates a regenerator structure configured for enhanced thermal efficiency according to an embodiment of the invention. The illustrated embodiments in **60** are generally suitable for magneto-caloric materials that are brittle and hence cannot be processed via machining or sintering. Regenerator **60** includes a thermally conducting material defining a plurality of micro fluidic channels **62-72** adjacent to each other. Non-limiting examples of thermally conducting material includes aluminum, copper and other material as discussed above. Various manufacturing techniques such as machining, electro-discharge machining, investment casting, wire drawing (by swaging or rolling) or sheet metal stampings, or extrusion may be used to form the fluid channels. Magneto-caloric material is disposed within multiple pockets **74-78** formed between said micro fluidic channels **62-72**. Heat exchange fluid configured to flow within the fluid channels and physically isolated from the magneto-caloric material **74-78**. Magneto-caloric material may include at least one of a granular, a powder or a high-density structure. In one embodiment, the plurality of fluid channels **62-72** is arranged in fin structure. Such an assembly magneto-caloric material disposed adjacent to the fluid channels are enclosed within a casing **80** that holds the magneto-caloric material in contact with the outer surface of the fluid channels. A fluid path is defined within the micro fluidic channels **62-72** to facilitate flow of a heat exchange fluid, wherein the magneto-caloric material in the pockets **74-78** and the heat exchange fluid are in thermal communication and physical isolation. Heat exchange fluid flowing through the fluid channels **62-72** is in thermal communication with the magneto-caloric material **74-78** via the thermally conducting material.

[0038] Secondary elements such as dimples, groves, threads, micro-fins, or multiple spiral coils may be disposed within the fluid channels to increase the flow rate and turbulence, and hence increase thermal efficiency. In one embodiment, the inner surface of the micro fluidic channels **62-72** is roughened to enhance heat exchange property of the micro fluid channels. Designing the fluid channel with corrugation that provides high surface area further enhance the heat exchange property. End-headers **82**, **84** are disposed at both ends of the fluid channels such that path for the heat exchange fluid is channelized into the fluid channels **62-72** and prevents fluid contact with the magneto-caloric material.

[0039] In a particular embodiment, the height and width of individual fluid channel, distance between the fluid channels, mass of magneto-caloric material is optimized for maximum thermal efficiency. A further zoomed in view of the fluid channel is illustrated by the reference numeral **86**. Dimensions of the micro fluidic channel such as width (**94**), height (**90**), and length (**92**) are optimized for achieving a desired flow rate of the heat exchange fluid. Fluid channels are designed, for example in a circular, a square, or a rectangular shape. Further, a higher channel aspect ratio is designed (channel aspect ration defined as the ratio of the channel length to the channel hydraulic diameter). In one embodiment, the channel aspect ratio from about 5 to about 30 and channel hydraulic diameter of about 0.1 mm to about 1 mm is provided for high heat transfer coefficient.

[0040] FIG. **8** illustrates arrangement of fluid channels and magneto-caloric material. The illustrated embodiments are an alternate arrangement of fluid channels and magneto-caloric material. The reference numeral **100** illustrates a cross-sectional view of regenerator defining a plurality of fluid channels **102** arranged in a honeycomb structure. Magneto-caloric material **104** is disposed adjacent to the fluid channels. The micro fluidic channels comprise similar dimensions as described in FIGS. **4** and **5**.

[0041] In another embodiment, the excitation field to magnetize and de-magnetize the magneto-caloric material is disclosed. FIG. **9** illustrates magnetizing profile according to an embodiment of the invention. Such excitation profile may be implemented in static design magneto-caloric systems. The magnetization profile **110** (having magnetic field (H) intensity on the y-axis) includes a first magnetic field **112** and **114** configured to generate a base excitation. The magnetic field profile **110** is configured to alternatively magnetize (during **112**) and demagnetize (during **114**) the magneto-caloric material. A magnetic source is configured to generate a high frequency magnetic field, for example, alternating current (AC) signal such as **116**, **118** that is configured to overlap with the base excitation magnetic field. Such high frequency excitation may oscillate magnetic domain walls within the magneto-caloric material about their static, equilibrium position and reduce the energy barrier to re-align domain wall. Thus by superimposing high frequency field on the base excitation, total power required to magnetize and demagnetize the magneto-caloric material is reduced. Multiple magnetizing profiles, such as illustrated by **120**, **122**, and **124** may be implemented. Magnetizing profile **120** includes the high frequency magnetic field **116** applied at the beginning of every magnetization cycle for partial time interval of about half the total magnetization cycle **126**. Similarly, magnetizing profile **122** implements an additional high frequency magnetic field **118** applied at the beginning of every demagnetization cycle for partial time interval of about half the total demagnetization cycle **128**. Alternatively, as illustrated by the reference numeral **124**, the high frequency magnetic field **130**, **132** may be applied just before the cyclic change during the magnetization-demagnetization cycle.

[0042] Advantageously, such regenerator structures have improved heat transfer efficiency. Thermally efficient regenerator reduces amount of magneto-caloric material required to achieve the specific cooling rate and hence reduction in size, weight and cost of the overall magneto-caloric system. Effective permeability of the magneto-caloric regenerators is enhanced (despite lower permeability of the magneto-caloric materials) by such regenerator design and fabrication. The micro fluidic channels have low-pressure drop, low fluid flow time and avoid contact between the fluid and the magneto-caloric material. High thermal diffusivity configuration of regenerators enables transient operation of the magnetic refrigeration cycle and conduct heat between the magneto-caloric material and heat transfer fluid. Pores in the magneto-caloric material, may be filled with suitable thermal pastes for enhanced transient response. Further, the fluid channels are designed to use extended surface contact with higher heat transfer area. Spiral coils within the fluid channels improve the heat transfer co-efficient. Hexagonal packing of miniature protrusions made of magneto-caloric material may be implemented for higher thermal diffusivity. Fluid channels that are designed to be circular, square, rectangular, or any other shape are designed for higher channel aspect ratios (Need to define thermal aspect ratio and proposed aspect ratio range) and lower channel hydraulic diameter (Need to define hydraulic diameter and proposed aspect ratio range) to provide high heat transfer coefficient. The magnetic intensity required to produce flux reduces with permeability improvements in magneto-caloric materials. Such structural designs leverage magnetic aspect ratio with respect to the magnetic field directed along length of the miniature protrusions by aligning the grains magnetically and enable magnetic domains to align along the flux lines, hence reduce the magnetic field intensity requirement. Such structures further help achieve compact size, lower weigh, are simpler in construction and hence economical to build. Avoiding direct contact of heat transfer fluids and magneto-caloric materials by such regenerator designs minimizes oxide or hydroxide layer formation.

[0043] While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

1. A regenerator comprising:

a thermal diffusivity matrix of magneto-caloric material comprising a plurality of miniature protrusions intimately packed to form a gap between the protrusions;

a fluid path defined within the gap to facilitate flow of a heat exchange fluid and efficient thermal exchange between the heat exchange fluid and magneto-caloric material; and

a first layer disposed on each of the miniature protrusion to physically isolate the heat exchange fluid and magneto-caloric material, wherein the first layer further comprise a soft magnetic material configured to simultaneously enhance a permeability and a thermal efficiency of the regenerator.

2. The regenerator of claim **1**, wherein said each miniature protrusion comprise a high aspect ratio such that the height of each miniature protrusion is at least more than 10 times the cross-section area of each said miniature protrusion.

3. The regenerator of claim **1**, wherein the thermal diffusivity matrix is subjected to an external magnetic field prior to assembling the miniature protrusions to align the spin within one or more magnetic domains of the magnet-caloric material.

4. The regenerator of claim **1** further comprising a magnet assembly to magnetize and de-magnetize the regenerator cyclically.

5. The regenerator of claim **1**, wherein the miniature protrusions comprise a plurality of miniature pin structures.

6. The regenerator of claim **1**, wherein the miniature protrusions comprise a plurality of miniature plate structures.

7. The regenerator of claim **1**, wherein the miniature protrusions are arranged in a honeycomb structure.

8. The regenerator of claim **1** further coupled to a load and a sink.

9. The regenerator of claim **8**, wherein the heat exchange fluid is configured to facilitate thermal exchange between the load and the sink.

10. A regenerator comprising:

a thermally conducting material defining a plurality of micro fluidic channels adjacent to each other;

a magneto-caloric material disposed within a plurality of pockets formed between said micro fluidic channels;

a fluid path defined within said micro fluidic channels, said fluid path facilitate flow of a heat exchange fluid, wherein the magneto-caloric material and the heat exchange fluid are in thermal communication and physical isolation.

11. The system of claim **10**, wherein the magneto-caloric material comprises at least one of a granular, a powder, or a high-density structure.

12. The system of claim **10**, wherein said micro fluid channels are arranged in a fin structure.

13. The system of claim **12** further comprising multiple spiral coils disposed within the micro fluid channels.

14. The system of claim **12**, wherein the micro fluid channels comprise roughened inner surface.

15. A magneto-caloric system comprising:

a regenerator comprising:

a magnetically aligned cluster of a magneto-caloric material, the cluster comprising miniature protrusions arranged intimately to form a gap between said miniature protrusions; and

a fluid path within said gap configured to exchange thermal units between a heat exchange fluid and the magneto-caloric material;

a magnet assembly to generate magnetic flux that magnetize and de-magnetize the regenerator cyclically;

a fluid circuit coupling a load, a sink, and the regenerator, wherein the heat exchange fluid facilitate exchange of thermal units between the load and the sink.

16. The magneto-caloric regenerator of claim **15** further comprising a first layer disposed around said each miniature protrusions.

17. The magneto-caloric regenerator of claim **16**, wherein the first layer is configured to simultaneously enhance the magnetic permeability and the thermal efficiency of the regenerator.

18. The magneto-caloric regenerator of claim **16**, wherein the first layer is configured to chemically isolate the magneto-caloric material from the fluid path.

19. The magneto-caloric regenerator of claim **15** further comprising an external magnetic field to align cluster of the magneto-caloric material

20. The magneto-caloric regenerator of claim **15**, wherein the fluid path is thermally coupled and physically isolated from the magneto-caloric material.

21. A magneto-caloric system comprising:

a regenerator made of magneto-caloric material configured to heat or cool when magnetically excited;

a magnetic assembly to generate a first magnetic field configured to excite the regenerator;

a second magnetic source to generate a high frequency magnetic field configured to excite the regenerator; and

a fluid circuit to facilitate flow of a heat exchange fluid though the regenerator configured to transfer thermal units between a load and a sink.

22. The system of claim **21**, wherein the magnetic field is configured to produce a magnetization and demagnetization cycle.

23. The system of claim **21**, wherein the high frequency magnetic field is configured to overlap the magnetic field for at least a partial interval of time.

24. The system of claim **23**, wherein high frequency magnetic field is configured re-align domain wall of the magneto-caloric material.

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