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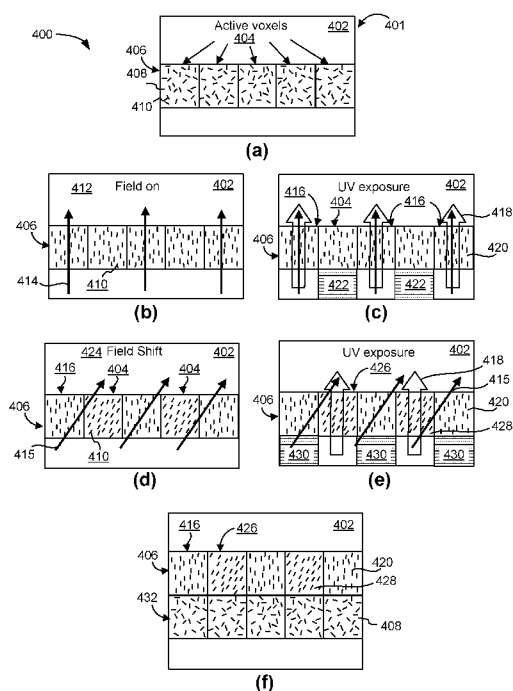


FIG. 4

(57) Abstract: A method of forming a three-dimensional structure includes forming a layer of resin comprising liquid crystal oligomers and a photoinitiator, applying a magnetic field to the formed layer in a predefined alignment direction for substantially aligning the liquid crystal oligomers in a first orientation; and exposing the formed layer to radiation for curing a first portion of the layer during application of the magnetic field thereby resulting in the first portion having liquid crystal elastomers substantially aligned in the first orientation. The method includes applying a second magnetic field to the formed layer in a predefined second alignment direction for substantially aligning uncured liquid crystal oligomers in a second orientation, and exposing the layer to radiation for curing a second portion of the layer during application of the second magnetic field thereby resulting in the second portion having liquid crystal elastomers substantially aligned in the second orientation.

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STEREOLITHOGRAPHY ADDITIVE MANUFACTURING OF MAGNETICALLY ALIGNED LIQUID CRYSTAL ELASTOMERS

[0001] This invention was made with Government support under Contract No. DE-AC52-07NA27344 awarded by the United States Department of Energy. The Government has certain rights in the invention. This invention was made with government support under 2011754 awarded by National Science Foundation (NSF) and under W911NF-17-1-0351 awarded by U.S. Army Research Office (ARO). The government has certain rights in this invention.

FIELD OF THE INVENTION

[0002] The present invention relates to additive manufacturing of liquid crystal elastomers, and more particularly, this invention relates to the magnetic alignment of liquid crystal elastomers to form a three-dimensional structure by stereolithography additive manufacturing techniques.

BACKGROUND

[0003] Additive manufacturing (AM) of liquid crystal elastomers (LCEs) is on the rise, as shown by the growing number of studies using direct ink write (DIW) of LCEs to form three-dimensional (3D) structures. However, DIW additive manufacturing techniques cannot achieve higher part resolution, increased part complexity, and 180° liquid crystal (LC) alignment control within local volume elements leading to 3D-to-3D shape change, which would benefit a wider range of application spaces. For example, DIW techniques may not form complex shapes such as octet truss, gyroid, etc. Moreover, DIW techniques have not demonstrated an LCE alignment for shape change in a 3D space distinct from a shape change in a two-dimensional (2D) space. There is a need to

extend LCE printing of 3D structures to stereolithography (SLA) vat polymerization. However, recent studies of printing LCEs using lithography techniques do not include alignment of the LC molecules, and thus, without alignment, the resultant parts have limited 3D-to-3D shape change properties. A process to provide layer-by-layer printing with precisely controlled LC alignment throughout a printed 3D part that allows a 3D transition of the part after printing remains elusive.

SUMMARY

[0004] According to one aspect, a method of forming a three-dimensional structure comprising liquid crystal elastomers includes forming a layer of resin comprising liquid crystal oligomers and a photoinitiator. The liquid crystal oligomers comprise at least one mesogen. The method includes applying a first magnetic field to the formed layer of resin in a predefined first alignment direction for substantially aligning the liquid crystal oligomers in a first orientation; exposing the formed layer to radiation for curing a first portion of the layer during application of the first magnetic field thereby resulting in the first portion having liquid crystal elastomers substantially aligned in the first orientation. The method further includes applying a second magnetic field to the formed layer of resin in a predefined second alignment direction for substantially aligning uncured liquid crystal oligomers in a second orientation, and exposing the layer to radiation for curing a second portion of the layer during application of the second magnetic field thereby resulting in the second portion having liquid crystal elastomers substantially aligned in the second orientation.

[0005] According to another aspect, a product includes a three-dimensional structure having a plurality of sequentially formed layers comprised of liquid crystal elastomers. The liquid crystal elastomers in at least a predefined portion of a first of the layers are substantially aligned in a first orientation, and the liquid crystal elastomers in at least a predefined portion of a second of the layers are substantially aligned in a second orientation. In addition, each of the portions of the three-dimensional structure is characterized as exhibiting a shape change in response to a stimulus, where the shape change is reversible.

[0006] Other aspects and advantages of the present invention will become apparent from the following detailed description, which, when taken in conjunction with the drawings, illustrate by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0007] FIG. 1 is a flow chart of a method, according to one aspect.
- [0008] FIG. 2A is a schematic drawing of one example of liquid crystal oligomer synthesis prior to magnetic alignment and UV crosslinking, according to one aspect.
- [0009] FIG. 2B is a series of schematic drawings of a magnified view of alignment of liquid crystal (LC) molecules, according to various approaches. Part (a) is a schematic drawing of an LC oligomer, part (b) is a schematic drawing of uncured, polydomain LC oligomers in a resin, part (c) is a schematic drawing of uncured, aligned nematic monodomain LC oligomers in a resin, and part (d) is a schematic drawing of a portion of cured, nematic monodomain LC elastomers (LCEs).
- [0010] FIG. 2C is a schematic drawing of the range of orientations of liquid crystal molecules, according to one aspect.
- [0011] FIG. 3 is a schematic drawing of a standard projection microstereolithography (PμSL) vat polymerization process.
- [0012] FIG. 4 is a schematic drawing of a magnetic alignment approach for voxel-by-voxel liquid crystal aligned SLA layers, according to one aspect. Part (a) depicts a layer of resin, part (b) depicts the application of a magnetic field in a predefined alignment direction, part (c) depicts exposure of predefined portions of the layer to a UV light to cure the resin, part (d) depicts the application of a different magnetic field in a different predefined alignment direction, part (e) depicts exposure of predefined portions of the layer to a UV light to cure the resin, and part (f) depicts addition of the next layer of uncured, unaligned resin adjacent to the cured layer.
- [0013] FIG. 5 is a series of schematic drawings of portions of three-dimensional structures, according to various approaches. Part (a) is a schematic drawing of a portion of a three-dimensional structure having a plurality of layers, part (b) is a schematic drawing of a portion of a three-dimensional structure having the orientation of LCs of voxels in the first and second layer along a similar predefined alignment direction, part (c) is a schematic drawing of a portion of a three-dimensional structure showing two layers having distinct voxels comprising LCs substantially aligned in different respective orientations, part (d) is a schematic drawing of a portion of a

three-dimensional structure with each layer having unidirectional alignment of LCs across the entire layer.

[0014] FIG. 6 is a schematic drawing of an actuation of a LCE structure, according to one aspect.

[0015] Part (a) of FIG. 7 is a schematic drawing of an apparatus of magnetic alignment of portions of LCEs in a layer, according to one aspect. Part (b) of FIG. 7 is a polarized optical image of a layer of cured LCEs having a predefined portion that has aligned LCEs in contrast to a portion that has randomly aligned LCEs, according to one aspect.

[0016] FIG. 8 includes plots of the magneto-rheology of a monomeric liquid crystal, according to one aspect. Part (a) depicts a plot of storage and loss modulus versus strain amplitude, part (b) depicts a plot of the storage modulus over time during the application of various magnetic field strengths, and part (c) depicts a plot of the ratio of storage modulus when magnetic field is present or not applied (G'_{on}/G'_{off}) during the application of increasing magnetic field strength.

[0017] FIG. 9 depicts a series of plots of the magneto-rheology of liquid crystal oligomers, according to one aspect. Each plot depicts a change in property over time during application of various magnetic field strengths. Part (a) depicts a plot of the magnetic flux, part (b) depicts a plot of storage modulus.

[0018] FIG. 10A depicts images of a polarized optical image of a layer of cured LCEs having an in-plane alignment, according to one aspect. Parts (c) and (d) are line drawings that correspond to the images of parts (a) and (b) in order to visualize the change in LCEs. Part (a) is an image of the layer, part (b) is an image of the layer rotated 45° relative to the cross polarizers, part (c) is a line drawing corresponding to the image of part (a), and part (d) is a line drawing corresponding to the image of part (b).

[0019] FIG. 10B depicts images of a polarized optical image of a layer of cured LCEs having an out-of-plane alignment, according to one aspect. Parts (c) and (d) are line drawings that correspond to the images of parts (a) and (b) in order to visualize the change in LCEs. Part (a) is an image of the layer, part (b) is an image of the layer rotated 45° relative to the cross polarizers, part (c) is a line drawing corresponding to the image of part (a), and part (d) is a line drawing corresponding to the image of part (b).

[0020] FIG. 11 depicts a plot of tensile testing of the cured LCE material having in-plane alignment and out-of-plane alignment, according to one aspect.

DETAILED DESCRIPTION

[0021] The following description is made for the purpose of illustrating the general principles of the present invention and is not meant to limit the inventive concepts claimed herein. Further, particular features described herein can be used in combination with other described features in each of the various possible combinations and permutations.

[0022] Unless otherwise specifically defined herein, all terms are to be given their broadest possible interpretation including meanings implied from the specification as well as meanings understood by those skilled in the art and/or as defined in dictionaries, treatises, etc.

[0023] It must also be noted that, as used in the specification and the appended claims, the singular forms "a," "an" and "the" include plural referents unless otherwise specified.

[0024] For the purposes of this application, room temperature is defined as in a range of about 20 °C to about 25 °C.

[0025] As also used herein, the term "about" denotes an interval of accuracy that ensures the technical effect of the feature in question. In various approaches, the term "about" when combined with a value, refers to plus and minus 10 % of the reference value. For example, a thickness of about 10 nm refers to a thickness of $10 \text{ nm} \pm 1 \text{ nm}$, a temperature of about 50 °C refers to a temperature of $50 \text{ °C} \pm 5 \text{ °C}$, etc.

[0026] It is also noted that, as used in the specification and the appended claims, wt.% is defined as the percentage of weight of a particular component relative to the total weight/mass of the mixture. Vol.% is defined as the percentage of volume of a particular compound relative to the total volume of the mixture or compound. Mol.% is defined as the percentage of moles of a particular component relative to the total moles of the mixture or compound. Atomic % (at.%) is defined as a percentage of one type of atom relative to the total number of atoms of a compound.

[0027] Unless expressly defined otherwise herein, each component listed in a particular approach may be present in an effective amount. An effective amount of a component means that enough of the component is present to result in a discernable change in a target characteristic of the ink, printed structure, and/or final product in

which the component is present, and preferably results in a change of the characteristic to within a desired range. One skilled in the art, now armed with the teachings herein, would be able to readily determine an effective amount of a particular component without having to resort to undue experimentation.

[0028] In addition, the present disclosure includes several descriptions of a “resin” used in an additive manufacturing process to form the inventive aspects described herein. It should be understood that “resins” (and singular forms thereof) may be used interchangeably and refer to a composition of matter comprising a plurality of oligomers, particles, small molecules, etc. coated with and dispersed throughout a liquid phase. In some inventive approaches, the resin may be optically transparent having a greater than 90% transmittance of light. In some inventive approaches, the resin is light sensitive where exposure to a particular light source changes the physical and/or chemical properties of the resin.

[0029] The following description discloses several preferred structures formed via photo polymerization processes, e.g., projection microstereolithography, photolithography, two photon polymerization, etc., or other equivalent techniques and therefore exhibit unique structural and compositional characteristics conveyed via the precise control allowed by such techniques. The physical characteristics of a structure formed by photo polymerization processes may include fabrication of a solid micro-structure having complex geometric arrangement of ligaments, filaments, etc. The formation of a three-dimensional structure includes exposing a resin to light, where a pattern in the photoresist is created by the exposing light.

[0030] The following description discloses several preferred aspects of ink formulations for forming a three-dimensional (3D) structure of liquid crystal elastomers (LCEs) having aligned liquid crystals in a predefined direction, the 3D structure being capable of a shape change, and/or related systems and methods.

[0031] In one general aspect, a method of forming a three-dimensional structure comprising liquid crystal elastomers includes forming a layer of resin comprising liquid crystal oligomers and a photoinitiator. The liquid crystal oligomers comprise at least one mesogen. The method includes applying a first magnetic field to the formed layer of resin in a predefined first alignment direction for substantially aligning the liquid crystal oligomers in a first orientation; exposing the formed layer to radiation for curing a first portion of the layer during application of the first magnetic field

thereby resulting in the first portion having liquid crystal elastomers substantially aligned in the first orientation. The method further includes applying a second magnetic field to the formed layer of resin in a predefined second alignment direction for substantially aligning uncured liquid crystal oligomers in a second orientation, and exposing the layer to radiation for curing a second portion of the layer during application of the second magnetic field thereby resulting in the second portion having liquid crystal elastomers substantially aligned in the second orientation.

[0032] In another general aspect, a product includes a three-dimensional structure having a plurality of sequentially formed layers comprised of liquid crystal elastomers. The liquid crystal elastomers in at least a predefined portion of a first of the layers are substantially aligned in a first orientation, and the liquid crystal elastomers in at least a predefined portion of a second of the layers are substantially aligned in a second orientation. In addition, each of the portions of the three-dimensional structure is characterized as exhibiting a shape change in response to a stimulus, where the shape change is reversible.

[0033] A list of acronyms used in the description is provided below.

2D	two-dimensional
3D	three-dimensional
AM	Additive manufacturing
DIW	direct ink writing
LC	Liquid crystal
LCE	Liquid crystal elastomer
ms	millisecond
mT	millitesla
nm	nanometer
PμSL	projection microstereolithography
SLA	stereolithography
T	Tesla
T _{NI}	Nematic-to-isotropic transition temperature
μm	micron
UV	ultraviolet
wt. %	weight percent

[0034] Liquid crystal elastomers (LCEs) combine the properties of liquid crystals (orientational order and mobility) and polymer networks (rubbery elasticity). Due to the coupling of the anisotropic liquid crystal (LC) molecules to elastomer networks, LCEs exhibit a reversible shape memory effect upon an anisotropic-to-isotropic transition, which can be triggered by external stimuli, such as temperature, light, electric field, etc. The resultant shape change may be determined by the alignment direction of the liquid crystals. Conventional methods are limited to alignment of LC molecules in two-dimensional LCE films that may be induced to shape change into three-dimensional space.

[0035] Moreover, current methods for printing LCEs are limited to direct ink write (DIW) additive manufacturing methods. DIW printing of LCEs involves shear and extensional forces during extrusion that unidirectionally align the LC molecules along the printing direction. The alignment of the liquid crystals in the LCE is randomized when heated above their nematic-to-isotropic transition temperature (T_{NI}), and then during extrusion, the LC molecules are aligned along the printing direction. As the strand is printed, it cools to room temperature and is cured with UV, thereby fixing the orientation of the LC molecule alignment. When heated, the shape change of the printed strand is limited to contraction along the filament axis and expansion perpendicular to the filament axis.

[0036] An additional drawback of DIW AM methods includes a restriction of feature size resolution. The feature size of DIW printed parts are limited by the diameter of the nozzle for extruding the filament. Thus, typical features sizes of DIW printed parts are about 250 microns (μm). There is a need for greater control of LC alignment beyond the as-deposited alignment afforded by DIW printing techniques to enable 3D-to-3D shape change for a wider range of application spaces, and a need for higher part resolution and increased part complexity.

[0037] In preferred approaches, as described herein, LCs are aligned in a predefined orientation, different than the orientation of the as-deposited alignment, during the process of printing and curing in order to set the LC molecules in an elastic network. In so doing, the LCEs respond to environmental stimuli and induce a shape change of the printed structure to an extent determined by a predefined orientation of the LC molecules in the LCE matrix. In one aspect, a method using a stereolithography (SLA) additive manufacturing technique is capable of forming a 3D printed part having LC molecules

substantially aligned according to a predefined orientation in the LCE matrix such that the LCE is capable of inducing a shape change with a higher actuation of strain % (e.g., up to about 50 % strain) in response to environmental stimuli. Shape change may be measured as strain in multiple directions. For example, in an extruded filament, when heated, the filament may contract along its axis and expand perpendicular to its axis. However, as described in various approaches herein, shape change in a 3D structure may occur in many directions according to a complex alignment map.

[0038] According to one aspect, the inherent dipole moment of LC molecules allows the LC molecules to substantially align in an orientation determined by an alignment direction of an applied magnetic field. However, some recent studies that attempted to align LCEs by applying a magnetic field during formation of the LCE material were unable to demonstrate that the formed material has the physical characteristic of shape change in response to a stimuli. In particular, an alignment of main chain LCEs using conventional processes have failed to exhibit shape change above a 2 % change in at least one dimension of the formed material. Specifically, SLA printing LCEs without aligning LCs during printing will likely result in a 3D structure that cannot undergo shape change.

[0039] In one aspect, a method combines forming a 3D structure layer-by-layer with predefined 360° magnetic alignment in an x - y plane control of LCs and having a predefined pattern of voxels, where each voxel is comprised of LC molecules substantially aligned in a predefined orientation. A voxel is a local volume element that adds a third dimension (z -dimension) to a two-dimensional (2D) pixel (x - y dimensions). Following alignment, each layer is cured using a voxel-by-voxel polarized light for curing the LCE to set the predefined alignment of the LCs into place. In one approach, a method is disclosed for magnetic alignment of LCE resin within SLA vat polymerization.

[0040] FIG. 1 shows a method **100** for forming a 3D structure having LCEs with selective 360° alignment control in the theta θ direction within the x - y plane, in accordance with one aspect. The printer apparatus may include a rotating magnetic field that may induce an azimuthal alignment angle in the z -direction. As an option, the present method **100** may be implemented to construct structures such as those shown in the other FIGS. described herein. Of course, however, this method **100** and others presented herein may be used to form structures for a wide variety of devices and/or purposes which may or may not be related to the illustrative aspects listed herein. Further, the methods

presented herein may be carried out in any desired environment. Moreover, more, or less operations than those shown in FIG. 1 may be included in method 100, according to various aspects. It should also be noted that any of the aforementioned features may be used in any of the aspects described in accordance with the various methods.

[0041] The method 100 may begin with operation 102 of forming a layer of resin where the resin includes liquid crystal (LC) oligomers and a photoinitiator. The LC oligomers may include at least one mesogen. In other approaches, the LC oligomers may include mesogens, chain extenders, and reactive end groups. In some approaches, broadly reactive LC mesogens may include both monomer form and oligomer form. In some approaches, the resin may include a photoinhibitor and/or a photoabsorber. The synthesis of an LC oligomer may include at least one mesogen having reactive end groups that combine with chain extender molecules to form a LC oligomer, e.g., a main chain liquid crystal oligomer, LC polymer, etc.

[0042] As illustrated in FIG. 2A, part (a), one example of the synthesis 200 of an LC oligomer 202 includes at least one mesogen 204 having reactive end groups 206 on each end of the mesogen reacted with amine chain extender molecules 208 to form an LC oligomer 202 having at least one amine chain extender molecule 208 positioned between each mesogen 204 of the main chain with reactive end groups 206 on each end of the LC oligomer (e.g., main chain liquid crystal oligomer, LC polymer, etc.). The mesogen 204 molecule has a lateral dipole moment 205. The rod-like molecule of the mesogen 204 positioned between end groups 206 with some degree of polarity that creates a dipole moment 205 that may be oriented substantially parallel along the alignment direction of an adjacent magnetic field.

[0043] In various approaches, the resin includes LC oligomers that may be cured as liquid crystal elastomers. In some approaches, the LC oligomers may include main chain LC oligomers, side chain LC oligomers, or a combination of main chain and side chain LC oligomers. In one approach, the resin includes LC oligomers formed with mesogens and chain extender molecules, where the mesogens have reactive end groups. In one approach of the formulation of a resin, an LC oligomer may include one repeat unit of the mesogen molecule. In other approaches of the formulation of the resin, the LC oligomer may include greater than one repeat unit of the mesogen molecule. Mesogens may be obtained commercially.

[0044] Theoretically, a maximum shape change of the formed 3D structure may be determined from the aspect ratio of the mesogen molecules of the LC oligomers. The structure of the mesogens may determine the aspect ratio and stiffness of the mesogen molecules. For example, a mesogen having 4 benzene rings is a stiffer molecule than a mesogen with 1 or 2 benzene rings. Upon stimulation, a mesogen molecule may reorient 90° upwards, and thus, a bigger aspect ratio of the mesogen molecule results in a greater degree of shape change. However, a higher aspect ratio of the mesogen molecules may result in a higher viscosity of the resin, and thus, a more rigid resin may inhibit printing efficiency. In a preferred approach, an aspect ratio (i.e., height to width) of the mesogens is about 3:1 to about 5:1. In some approaches, main chain LC oligomers include rigid LC mesogens with a reactive end group on each end for curing (e.g., crosslinking) the LC oligomers into LCEs. In some approaches, each LC oligomer of the resin may include about 3 to 15 mesogen molecules along the backbone of the LC oligomer.

[0045] Different mesogens may have different nematic-to-isotropic transition temperatures. For example, mesogens having a higher molecular weight, e.g., higher than a small molecule (i.e., a small molecule being < 900 daltons), may result in a higher nematic-to-isotropic transition temperature. For mesogens having a nematic-to-isotropic transition temperature of 100 °C, the ratio of different mesogens may be used to lower the nematic-to-isotropic transition temperature below 100 °C. Alternatively, the nematic-to-isotropic transition temperature of an LC oligomer may be raised by incorporating more rigid mesogen molecules as a part of the oligomer.

[0046] In some approaches, the ratio of mesogens to chain extender molecules in the LC oligomer (e.g., LC polymer) that comprise the resin may characterize mechanical properties of the 3D structure formed using the resin. For example, the ratio of mesogens to chain extenders may determine the extent, type, etc. of shape change of the formed 3D structure. In various approaches, the chain extender molecules between the mesogens may include amines, thiols, etc. In one approach, a ratio of mesogen to the chain extender may be about 1:1. In some approaches, a higher ratio is preferred, for example around 1.4:1 up to 2:1 mesogen to chain extender. An LC oligomer having a higher ratio of mesogens to chain extender results in shorter polymer chains, whereas an LC oligomer having a lower ratio of mesogens to chain extenders results in longer polymer chains. An aligned and cured LCE from longer LC oligomer chains may result in a 3D structure having a capability of a larger shape change in response to external stimuli.

[0047] The LC oligomers, LC polymers, etc. are formed by a chain extension process including the mesogens and chain extenders with reactive end groups on each end of the formed LC oligomers. The LC oligomers are preferably formed before being added to the printing process as a resin. In some approaches, a resin may include a mixture of mesogens having reactive end groups but without a chain extender, however, the resin may be highly viscous, rigid, etc.

[0048] In one approach, the resin may include an effective amount of an additive for assisting the alignment of the LC oligomers during application of a magnetic field. In various approaches, the additive may include cellulose nanocrystals, carbon nanotubes, magnetically addressable platelet solid filler particles, etc. In some approaches, the additive may be included for assisting in resultant actuation strain, shape change, etc. with the magnetic field.

[0049] In one approach, the additive may be included to increase the magnetic susceptibility of the LC oligomers. For example, in one approach, the additive is a magnetic filler. The presence of a magnetic filler in the resin increases the magnetic susceptibility of the LC oligomers such that a lower magnetic field strength, lower than 100 millitesla (mT) may induce alignment of the LC oligomers. Alignment of the magnetic fillers in the resin would provide an alignment platform for the LC oligomers. For example, the LC oligomers align orthogonally to the alignment of the magnetic fillers such that the LC oligomers use the aligned magnetic as an anchoring site. As another example, functionalized magnetic filler may force the LC oligomers to align parallel to the alignment of the magnetic fillers. Magnetic fillers may include nanosized magnetic particles (nanoparticles), magnetic platelets, aluminum flakes, carbon fibers, etc.

[0050] In some approaches, the resin may include a photoinhibitor. In one approach, a photoinhibitor may extend the pot life of the resin to about 24 hours or greater. In some approaches, a photoinhibitor may be included for controlling the print resolution in the x and/or y direction. In one approach, a photoabsorber may be included for controlling the print resolution in the z -direction. Without wishing to be bound by any theory, it is believed that the inherent dipole moment of some photoabsorbers (e.g., Sudan I) may cause these photoabsorbers to be susceptible to orientation according to an alignment direction of the applied magnetic field.

[0051] In one approach, method **100** may include heating the resin to a temperature below the nematic-to-isotropic transition temperature of the mesogen for forming the

layer of resin. In preferred approaches, the resin is heated to reduce the viscosity of the resin and increase the mobility of the LC oligomers. In another approach, the method may include heating the resin to a temperature above the nematic-to-isotropic transition temperature of the mesogen in order to form a portion, voxel, etc. of the layer that may not undergo a shape change in response to a stimulus. The temperature may be sufficient to lower the viscosity of the resin without affecting a phase change of the resin (e.g., below the nematic-to-isotropic temperature of the LC oligomers). The temperature may be determined by the specific formulation of the LC resin. In a preferred approach, the printing apparatus includes a chamber for heating the bath, vat, etc. of resin. In some approaches, the resin may be heated to a temperature in a range of greater than 50 °C to less than 100 °C. The desired temperature may be determined by the viscosity and nematic-to-isotropic transition temperature of the formulation of the resin.

[0052] In another approach, the method **100** may include no heat applied to the resin while forming the layer of resin. The temperature of the resin may remain about room temperature during the forming of a three-dimensional structure comprising aligned LC elastomers. In one approach, the LCE may have a lower nematic-to-isotropic temperature such that the temperature of the process of forming a layer may be slightly above or at room temperature. Preferably, the process does not include a heating step. In one approach, no heat is applied during the process.

[0053] In some approaches, the layer may be formed according to a predefined pattern of the printing apparatus. For example, the layer may be a 2D slice as determined from a 3D model of the 3D structure to be printed. The layer may be a geometric shape according to the 2D slice of the 3D model. For example, a hollow sphere may be printed by a series of layers where the first layer is a circle, and subsequent layers are rings, and the final layer is a circle. In various approaches, the resolution of the features of each layer may be determined by the lithography additive manufacturing process. For example, the resolution of features of a layer using a Fortify printer may have a pixel pitch of 75 microns (μm).

[0054] As illustrated in part (a) of FIG. **2B**, the synthesis **220** of main chain LC oligomers **222** includes the combination of mesogens **224** having reactive end groups **226** with chain extender molecules **228** to form an LC oligomer **222** having at least one chain extender molecule **228** positioned between the mesogens **224** and a reactive end group **226** positioned at each end of the LC oligomer **222**.

[0055] Part (b) of FIG. 2B illustrates a portion of a formed layer of LC oligomers 222 prior to alignment. The LC oligomers 222 are present in the layer as a polydomain of uncured oligomers, the polydomain comprising a plurality of domains 230, 232 of LC molecules, (e.g., mesogens 224). For illustrative purposes only, the individual domains 230, 232 are defined by a dashed line between the domains. A domain 230 represents a group of LC molecules substantially aligned in the same orientation. The as-deposited alignment of the resin as a layer may include a plurality of domains 230, 232, having different, randomly aligned LC molecules, and each domain having at least one mesogen 224 aligned along a similar orientation. The polydomain is undefined and formed in the absence of application of a magnetic, electric, electromagnetic, etc. field. A polydomain is the isotropic state where all LCs are randomly aligned, i.e., the alignment is undefined.

[0056] In one approach, a stereolithography printing technique allows orientation of liquid crystal molecules layer-by-layer during the printing process by using magnetic alignment during the formation of each layer of LCEs. The inherent dipole moment of liquid crystals, as illustrated in FIG. 2A, may be exploited when a magnetic, electric field, electromagnetic field, etc. is applied. Looking back to FIG. 1, operation 104 of method 100 includes applying a first magnetic field to the formed layer of resin in a first predefined alignment direction for substantially aligning the liquid crystal oligomers in the first orientation. The predefined alignment direction may be selected from one direction of 360° alignment directions. For example, the predefined alignment direction of the magnetic field may be horizontal relative to the build plate (i.e., parallel to the x - y plane of the build plate), vertical relative to the build plate (i.e., perpendicular to the x - y plane of the build plate), at an acute angle relative to the build plate (e.g., slanted), at an obtuse angle relative to the build plate), etc.

[0057] Referring to FIG. 2C, an orientation direction of the liquid crystal molecules, e.g., a mesogen 224 molecule, may be defined by a magnetic director alignment. A dimensionless unit vector, e.g., liquid crystal director $\vec{n}$ describes the predominant orientation direction of nearby liquid crystals. A liquid crystal director $\vec{n}$ may be decomposed into spherical components as follows:

$$\vec{n} = \begin{cases} n_x = \cos \theta \sin \phi \\ n_y = \sin \theta \sin \phi \\ n_z = \cos \phi \end{cases}$$

[0058] where θ varies between 0° and 360° , and ϕ varies between 0° and 180° . A magnetic field map may be designed to target specific $\vec{n}$ directions. According to various approaches, a product may be formed voxel-by-voxel where each voxel has LC molecules oriented in unique predefined $\vec{n}$ direction. The LC molecules may be aligned in the x - y plane in 360° theta (ϕ) direction. The LC molecules may be aligned in the x - y plane in 360° theta (θ) direction. As illustrated in part (c) of FIG. 2B, for example, application of a magnetic field to the formed layer of resin in a predefined alignment direction substantially aligns the LC molecules into a nematic monodomain of LC molecules in an orientation determined by the magnetic alignment direction 234. The orientations of a majority of, and preferably at least 90 % of, the mesogens 224 are substantially aligned (e.g., within 10° of each other, preferably) in a first predefined alignment direction 234 relative to some reference, e.g., the plane of deposition of the layer.

[0059] According to some approaches, the orientation of the aligned LCs may be defined as the direction along which the longitudinal axis of the mesogen align. In other words, the orientation of the longitudinal axis of the mesogen molecule is substantially aligned along the alignment direction of the magnetic field. In some approaches, the alignment direction of the magnetic field may be tuned for a specific orientation of the bent core mesogens that are biaxial.

[0060] In some approaches, the duration of time for substantially aligning the LC oligomers of the resin in one orientation according to a respective predefined alignment direction of an applied magnetic field may be less than 120 seconds. In other approaches, the duration of time of substantially aligning the LC oligomers may be less than 60 seconds, less than 30 seconds, etc. In an exemplary approach, the duration of time for substantially aligning the LC oligomers during application of a magnetic field may be less than 10 seconds. A surprising and unexpected finding in light of the highly viscous composition of the resin is that orientation of the LC oligomers in the resin according to the alignment direction of the applied magnetic field may occur in the short duration of time of less than 10 seconds. Moreover, in some approaches, a lower intensity of field strength of the applied magnetic field results in alignment of greater than 90 % of LC oligomers in less than 10 seconds. For example, in an exemplary approach, a field strength from less than 0.06 tesla (T) to 0.01 T is sufficient to substantially align the LC

oligomers according to the alignment direction of the applied magnetic field in less than 10 seconds.

[0061] In some approaches, application of a magnetic field strength of 0.10 T or greater may be critical for aligning LC molecules in a single LC resin at a temperature above the nematic-to-isotropic temperature of the LC resin. In one approach, for a resin that includes an additive to increase magnetic susceptibility, LC oligomers may be aligned during the application of a magnetic field strength of less than 0.10 T. In various approaches, the first and the second magnetic field may have a magnetic field strength of at least 0.100 Tesla. In one approach, application of a critical magnetic field strength at 0.10 T or greater, alignment of the LC oligomers may be aligned almost instantly, within about 5 seconds. In other approaches, application of a magnetic field strength less than 0.10 T to a resin that does not include an additive, the duration of time to result in a uniform alignment of LC oligomers throughout the resin may be up to about 100 seconds.

[0062] In one approach, the duration of time for substantially aligning the LC oligomers in an orientation determined by the alignment direction of the magnetic field includes the time point of turning on the magnetic field until the time point wherein greater than 90 % of the active uncured LC oligomers in the layer are substantially aligned to the respective orientation determined by the alignment direction of the applied magnetic field. In some approaches, the duration of time for substantially aligning the LC oligomers in a predefined portion may include a duration of time measured from a time point of turning on the applied magnetic field until the time point of exposing the predefined portion to radiation, e.g., a light, for curing the aligned LC oligomers. An advantage of the short durations of time, e.g., less than 10 seconds, for greater than 90 % of active LC oligomers to be substantially aligned in one orientation includes increased printing efficiency, e.g., faster printing, of each layer of a 3D structure.

[0063] Referring back to FIG. 1, operation **106** of method **100** includes exposing the formed layer to radiation for curing a first portion of the layer during application of the first magnetic field thereby resulting in the first portion having liquid crystal elastomers substantially aligned in a first orientation determined by the alignment direction of the first magnetic field. In some approaches, the radiation may preferably be a light, a laser, a beam, etc. The LC oligomers have reactive functional end groups that enable crosslinking during exposure to radiation, e.g., UV light, and incorporate the LC oligomers into a cured liquid crystal elastomer network. In sharp contrast, magnetic alignment of particles

that are not functionalized with a crosslinkable ligand, e.g., filler particles, cannot form a crosslinked network, and typically rely on a surrounding crosslinkable material to form a network around the aligned particles to hold the aligned particles in place.

[0064] In various approaches, a light for curing the resin may be directed to a portion of the layer having LC oligomers substantially aligned to a first orientation determined by the applied magnetic field. The light may be directed onto the predefined portion by using a projector, masking the layer for exposing the portion to be cured, etc. The wavelength of the light is within a range for causing the end groups of the LC oligomers to crosslink and form a matrix LCE material. The wavelength for curing the aligned LC oligomers may be defined by the photoinitiator included in the resin. In one approach, curing the aligned LC oligomers includes exposing the aligned liquid crystal oligomers to a light at a wavelength in the UV spectrum, e.g., in a range of greater than about 200 nanometers up to about 389 nanometers. In one example, and not meant to be limiting in any way, the formulation of the resin may include a phosphine oxide photoinitiator, such as 2,4,6-trimethylbenzoyldiphenylphosphine oxide, can initiate crosslinking at 405 nm.

[0065] As illustrated in part (d) of FIG. 2B, the layer is exposed to a light for curing the resin during application of the magnetic field in a predefined alignment direction. The exposure to the light causes the reactive end groups 226 of the LC oligomer 222 to crosslink and form LC elastomers (LCEs) 236. The LCEs 236 are formed as a cured, nematic monodomain, e.g., a crosslinked and aligned LCE network.

[0066] Referring back to FIG. 1, operation 108 of method 100 includes applying a second magnetic field to the formed layer of resin in a predefined second alignment direction for substantially aligning the uncured liquid crystal oligomers to a second orientation. In a preferred approach, the predefined first alignment direction of the first magnetic field is different than the predefined second alignment direction of the second magnetic field.

[0067] Operation 110 of method 100 includes exposing the layer to radiation for curing a second portion of the layer during application of the second magnetic field thereby resulting in the second portion having liquid crystal elastomers substantially aligned to the second orientation.

[0068] In various approaches, third, fourth, etc. portions, e.g., voxels, of the layer may have the uncured LC oligomers of the third, fourth, etc. portion substantially aligned to an orientation determined by a predefined alignment direction of a different applied

magnetic field. Each layer includes a plurality of portions, e.g., voxels, where LC molecules are substantially aligned to a respective orientation of each respective portion. In various approaches, the number of orientations per layer may be limited only by the size of the sample, voxel, portion, etc.

[0069] In further approaches, method **100** includes forming a second layer of resin adjacent to the layer of LCEs, where the LCEs have been substantially aligned and cured in operations **104**, **106**, **108**, and **110**. A next operation may include applying a third magnetic field to the formed second layer of resin in a third predefined alignment direction for substantially aligning the LC oligomers of the resin to a third orientation. In another approach, the third magnetic field may have the same alignment direction as the first magnetic field, as described for operation **104**. In yet another approach, the third magnetic field may have the same alignment direction as the second magnetic field, as described for operation **108**.

[0070] During the application of the third magnetic field, the formed second layer may be exposed to a radiation for curing a first portion of the second layer thereby resulting in the first portion of the formed second layer having LCEs substantially aligned to the third orientation determined by the alignment direction of the third applied magnetic field. The second layer may comprise a plurality of portions having LCs substantially aligned to a respective orientation of each respective portion. The alignment direction of each applied magnetic field may be determined as a target alignment direction as described in FIG. **2C**.

[0071] The method of forming a 3D polymer structure is highly scalable and compatible with additive manufacturing (e.g., 3D printing). According to a method described herein, the 3D structure may be formed using a lithography-based additive manufacturing (AM) system. In some approaches, AM techniques such as projection micro-stereolithography (PμSL) may be employed. A PμSL system **300**, as illustrated in FIG. **3**, is a lithography-based technique where 2D slices, layers **302** of a 3D model **304** of a 3D object **306** are projected into a vat of photosensitive resin **308** with UV light **310**, forming the final 3D structure **312** layer-by-layer. For example, each layer **314** may be formed according to a predefined pattern determined by a layer **302** of a 3D model **304**. A 3D model **304** of the structure, object **306**, etc. is divided into a plurality of layers **302**, each layer **314** formed according to a predefined pattern determined by a layer **302** of the 3D model **304**. Printing with PμSL provides advantages of printing increased part

complexity and resolution. Moreover, decreasing the strut diameters of a 3D printed structure while maintaining structural integrity will allow for faster actuation times of shape change of the structure.

[0072] For forming a 3D structure **312**, the orientations of alignment of LCs in each layer **314** of resin **308** may correspond to a predefined pattern of an associated layer **302** of a 3D model **304**. In various approaches, the product has physical characteristics of formation by an additive manufacturing technique. In various approaches, physical characteristics may include filaments arranged in a geometric pattern, a patterned outer surface defined by stacking filaments, etc. Thus, using these additive manufacturing techniques allows engineering of parts and production of optimal geometry for shape change, mechanical strength, etc.

[0073] In one approach, the lithography technique may be a bottom-up building platform such that the light beam delivery approaches the build plate from the top, e.g., the PμSL system, as illustrated in FIG. **3**. In another approach, the lithography technique may be a top-down building platform such that the light beam delivery approaches the build plate from the bottom, e.g., the Fortify printer, as shown illustrated in FIG. **4**.

[0074] In one approach, method **100** of FIG. **1** of forming a 3D structure may include layer-by-layer printing using SLA printing techniques that results in LCEs substantially aligned to an orientation determined by a predefined alignment direction of an applied magnetic field during the printing process. A 3D structure has a plurality of layers, each layer having a plurality of portions, each portion having LCEs substantially aligned to an orientation determined by a predefined alignment direction of an applied magnetic field. As an example, FIG. **4** illustrates a method **400** of aligning LCEs during an SLA print using magnetic alignment to exploit the inherent dipole moment of LCs and align the LCs along the direction of the applied magnetic field. The magnetic alignment approach of the method **400** as illustrated in FIG. **4** uses a bottom-up lithography-based system while applying a magnetic field via solenoids to align material in each layer followed by subsequent UV exposure to lock the alignment in place. In other approaches, magnetic alignment may be employed with a top-down printing approach described in a PμSL system. The following approach describes substantially aligning LC molecules to an orientation determined by a predefined alignment direction of an applied magnetic field. The process of aligning LCs is voxel-by-voxel to allow the resultant printed 3D structure to undergo a high degree of shape change.

[0075] As illustrated in part (a), the method 400 begins with forming a layer 406 of resin 408 having LC molecules 410. The alignment of LCs as-deposited have an orientation in nonspecific directions, e.g., the LCs are isotropic. The LCs may group in sub domains such that the layer has a polydomain of LCs. The printing method may form a predefined portions of the layer on a build plate 402 of the printing apparatus 401, where each predefined portion includes at least one voxel 404. The voxels 404 may be described as active voxels having LCs that are not substantially aligned to a single orientation, rather the LCs of the active voxel are unaligned being oriented in multiple non-specific directions.

[0076] Part (b) illustrates the application of a first magnetic field 412 in a predefined first alignment direction 414, where the first magnetic field 412 is applied to the layer 406 of resin 408. The first alignment direction 414 of the first magnetic field 412 induces the LCs 410 to substantially align to a first orientation determined by the first alignment direction 414 of the first magnetic field 412. The first alignment direction of the applied magnetic field may be predefined by a 3D model of the desired printed 3D object.

[0077] As illustrated in part (c), while the first magnetic field 412 is applied to the layer 406, at least one predefined portion 416 is exposed to a light (418, large arrows) for curing the LC oligomers of the resin 408 to form an LCE 420 matrix having LCs 410 substantially aligned to a first orientation determined by the first alignment direction 414. In some approaches the shape, dimensions, etc. of the portion, voxel, etc. to be cured by light may be determined by a 3D model of the desired printed 3D object. In one approach, the light may be projecting illumination, e.g., UV light, from a digital light projector. The light is projected on the at least one predefined portion of the aligned LC oligomers of the resin. In another approach, the light 418 may be projected on the layer 406 of LC oligomers substantially aligned to an orientation determined by the first alignment direction 414 such that each portion 416 is defined according to a respective mask 422 applied to the formed layer during the respective exposure of the layer 406 to the light 418. The masked portions block the active voxels 404 having uncured resin 408 from curing when the layer 406 is exposed to the light 418. The masks may be removed after curing the predefined portions.

[0078] A second magnetic field 424 having a predefined second alignment direction 415 may be applied to the layer 406 of resin 408, as illustrated in part (d) of FIG. 4. As illustrated, the second magnetic field 424 has a field shift in alignment direction from the

alignment direction of the first magnetic field **412**, where the predefined second alignment direction **415** is different from the predefined first alignment direction **414**. The LCs **410** in the uncured portions, voxels **404**, etc. become substantially aligned to a second orientation determined by the second alignment direction **415** of the second magnetic field **424**. The cured portions **416** having LCEs **420** substantially aligned to a first orientation determined by the first magnetic field **412** are not affected by the application of the second magnetic field **424** and substantially aligned to the first orientation determined by the first alignment direction **414** during application of the second magnetic field **424**.

[0079] As illustrated in part (e), while the second magnetic field **424** is applied to the layer **406**, the predefined portion **426** is exposed to a light (**418**, large arrows) for curing the LC oligomers of the resin **408** to form an LCE **428** matrix having LCs **410** substantially aligned to a second orientation determined by the second alignment direction **415** of the second magnetic field **424**. In one approach, the light may be projecting illumination, e.g., UV light, from a digital light projector. The light is projected on the at least one predefined portion of the aligned LC oligomers of the resin. In another approach, the light **418** may be projected on the layer **406** of aligned LC oligomers such that each portion **426** is defined according to a respective mask **430** applied to the formed layer during the respective exposure of the layer **406** to the light **418**. The masks may be removed after curing the predefined portions.

[0080] Upon completion of substantially aligning the LCs **410** to respective orientations of each portion and curing the LCE material in portions **416**, **426** of the first layer **406**, a second layer **432** of resin **408** may be formed adjacent to the first layer **406** on the build plate **402**, as illustrated in part (f) of FIG. 4. The first layer **406** includes portions **416**, **426** having LCEs **420**, **428**, respectively, substantially aligned to a respective orientation according to the respective predefined alignment direction of each applied magnetic field.

[0081] In one approach, the second layer **432** may include predefined portions similar to the predefined portions of first layer **406**. The LC oligomers of the predefined portions are substantially aligned to a respective orientation determined by the respective alignment direction of the applied magnetic field and set by UV exposure as illustrated in parts (b) to (e) of FIG. 4. In another approach, the second layer may include portions as defined by a predefined pattern determined by a 2D slice (e.g., layer) of a 3D model. The

method **400** and various approaches are by way of example only and are not meant to be limiting in any way.

[0082] FIG. **5** depicts a series of schematic diagrams of a side view of a portion of products **500, 501, 520, 540**, in accordance with various aspects. As an option, the present products **500, 501, 520, 540** may be implemented in conjunction with features from any other inventive concept listed herein, such as those described with reference to the other FIGS. Of course, however, such products **500, 501, 520, 540** and others presented herein may be used in various applications and/or in permutations which may or may not be specifically described in the illustrative aspects listed herein. Further, the product **500, 501, 520, 540** presented herein may be used in any desired environment.

[0083] According to one aspect, a 3D structure has a plurality of layers comprised of LCEs. A plurality of layers may be defined as a product having more than one layer, for example, two layers, three layers, four layers, etc. In various approaches, the number of layers is determined by a predefined three-dimensional model of the product. For example, as illustrated in part (a) of FIG. **5**, a product **500** includes a portion of a 3D structure having plurality of layers, each layer having a plurality of voxels, and each voxel comprising LCEs substantially aligned in an orientation determined by a predefined alignment direction. Parts (b) through (d) illustrate examples of layers of a portion of a 3D structure and the orientation of aligned LCEs of each voxel according to a predefined alignment direction. The alignment orientation of the LCEs in parts (a) through (d) represent alignment of LCEs parallel to the plane of deposition of each layer. Each pattern illustrated in the figures represents a predefined alignment orientation but is not meant to define an orientation and thus each pattern is for illustration purposes only.

[0084] Part (b) of FIG. **5** illustrates a schematic drawing of a portion of product **501** having a plurality of sequentially formed layers, showing two layers **504, 506** comprised of LCEs **508**. In one approach, the 3D structure **502** has a layer **504** comprised of LCEs **508** present in at least a predefined portion **510**, e.g., a voxel. The LCEs **508** in a portion **510** of the first **504** layer are substantially aligned in a predefined first orientation **512**. In one approach, the orientations of a majority of, and preferably at least 90 % of, the LCEs **508** in a predefined first portion **510** of a first layer **504** are substantially aligned in a predefined first orientation **512** relative to some reference, e.g., the plane of deposition of the layer. For example, as used in some approaches described herein, orientations being

substantially aligned with a direction of the means, e.g., the LC molecule, mesogens, etc. that the mean longitudinal axes of the items so oriented are, on average, within 45° of the direction, preferably within 30° of the direction, more preferably within 15° of the direction, ideally within 10° of the direction.

[0085] A predefined orientation of the LC molecules of the LCE may be selected from a 360° alignment control in an x-y plane. For example, the orientation direction of the LC molecules may be any one of a radial direction in a 360° rotation of the theta direction, as illustrated in FIG. 2C. The predefined first orientation **512** may be different than the orientation of the as-deposited alignment of the LCEs **508**.

[0086] In one approach, LCE **508** are substantially aligned in a second orientation **513** in a predefined second portion **516** of the first layer **504** that may be different than the first orientation **512** of the LCEs **508** in the portion **510** of the same layer **504**. In one approach, at least 90 % of the LCEs **508** in the predefined second portion **516** of the first layer **504** are substantially aligned in the orientation **513** that is different than the first orientation **512**.

[0087] In one approach, the 3D structure **502** includes a second layer **506** adjacent the layer **504**. In one approach, the LCEs **508** are substantially aligned in a predefined second orientation in a predefined portion **514** of the second layer **506**. In one approach, the second orientation may be the same as the as the first orientation **512**, where the first predefined orientation **512** is different than the orientation of the as-deposited alignment of the LCEs **508**. The as-deposited alignment of the LCEs may be defined as the orientation of the LCEs following deposition of the resin during formation of a layer. In some approaches, the orientation of the as-deposited LCEs may include non-specific, isotropic, orientations of the LCEs at formation of the layer of the 3D structure in the absence of any aligning effects (e.g., magnetic field, photoalignment, etc.).

[0088] In one approach, the LCEs **508** in a portion **518** of the second layer **506** are substantially aligned in a predefined orientation **513** that may be different than the first orientation **512**.

[0089] In one aspect, as illustrated in a schematic drawing of a portion of a product **520** in part (c), a 3D structure **522** has a plurality of sequentially formed layers **524**, **526** comprised of LCEs **528** where the LCEs of each of the portions of each of the layers are substantially aligned in an orientation specific to each portion, respectively. For example, the LCEs **528** present in one portion **530** of the first layer **524** are substantially aligned in

a first orientation **512**. As described herein, the orientations of a majority of, and preferably at least 90 % of, the LCEs **528** are substantially aligned (e.g., within 10° of each other, preferably) in a respective orientation direction relative to some reference, e.g., the plane of deposition of the layer. In one approach, a predefined orientation may be selected from a 180° alignment control, e.g., the orientation direction may be any one of a radial *x-y* planar direction in a 360° rotation, as illustrated in FIG. **2C**. Each predefined orientation of the LCEs for each portion may be different than the as-deposited alignment direction of the LCEs **528**.

[0090] The LCEs in a predefined second portion of the layer are substantially aligned along a different orientation than the LCEs of a different, adjacent, etc. portion of the same layer. For example, adjacent to the first portion **530**, the LCEs **528** in a second portion **534** of the same layer **524** are substantially aligned in an orientation **515** that is different than the first orientation **512** of the LCEs **528** in the portion **530**.

[0091] In a second layer **526**, the LCEs **528** in another portion **532** are substantially aligned in an orientation **513** that may be different than the first orientation **512** and different from the second orientation **515**. Further, each of the orientations **512**, **513**, **515** may be different than the non-specific orientation of the as-deposited alignment of the LCEs **528**.

[0092] According to various aspects, the lithography-based technique of using a DMD to define each voxel of a printed layer allows the printed 3D structure to have a contiguous region of aligned LCEs in one of the portion has a minimum dimension as determined by the lithography-based printing apparatus. In some approaches, the maximum dimensions (e.g., height, width, depth) of the contiguous region is substantially equal to the dimensions of a voxel of the printed structure. In an exemplary approach, a contiguous region of aligned LCEs has a minimum of about 75 μm per pixel pitch, where a pixel pitch is defined as a dimension of one pixel, one voxel, one portion, etc. For example, a contiguous region of aligned LCEs **528** of portion **536** of layer **524** has a minimum dimension, e.g., width d_w , thickness, d_{th} , etc. of about 75 μm.

[0093] According to one approach, as illustrated in a schematic drawing of a portion of product **540** in part (d), a 3D structure **542** has a plurality of sequentially formed layers **544**, **546** comprised of LCEs **548** where a portion may extend along the entire layer. For example, the LCEs **548** present in the first layer **544** are substantially aligned in a first orientation **512** and a portion **550** extends along the entire layer **544**. The LCEs **548**

present in the second layer **546** are substantially aligned in a second orientation **513** and a portion **552** extends along the entire layer **546**. In one approach, the LCEs **548** in the second layer **546** are substantially aligned in an orientation that may be different than the orientation of the LCEs **548** in the first layer **544**.

[0094] The illustrations of FIG. **5** are by way of example only and are not meant to be limiting in any way. Each aspect may have a plurality of sequentially formed layers and a plurality of portions determined by the 3D model of the structure being printed, and each orientation of the LCEs for each of the portions may be predefined according to the application of the structure.

[0095] According to various aspects, the 3D structure is characterized as exhibiting a shape change in response to a stimulus. In various approaches, each of the portions of the 3D structure may be characterized as exhibiting a shape change in response to a stimulus. The shape change in the 3D structure may be realized with a formulation having a high actuation strain %, e.g., up to about 50 % strain. The shape change may be reversible. In one approach, the shape change is represented by a greater than 5 % volumetric change of the 3D structure. In one approach the shape change is represented by a greater than 5 % change in at least one dimension of the 3D structure, e.g., the length in a longitudinal direction, the width perpendicular to the length of the 3D structure, the thickness of the 3D structure, etc.

[0096] FIG. **6** depicts a schematic drawing of an actuation **600** of an LCE structure **602**, according to one approach. A structure **602** in an as-formed state **604** has a width W_0 , length L_0 , and height H_0 . In the magnified view **606** of the LCE matrix **608**, the LC molecules **610** in a nematic state such that the LC molecules **610** are substantially aligned according to a predefined orientation **612**. Upon stimulation of the LCE structure **602**, the LCE structure **602** undergoes a shape change such that the stimulated form **614** of the LCE structure **602** now has change in width W and height H , and in particular a significant change in the length L of the structure. The magnified view **616** of the LCE matrix **608** shows the LC molecules **610** have nonspecific orientations in an isotropic state. Removing the stimulant, turning off the stimuli, etc. causes the LCE structure **602** to return to the resting, as-formed state **604**, e.g., a programmed aligned state, in which the LC molecules **610** are substantially aligned to a predefined orientation **612**.

[0097] Experiments

[0098] FIG. 7 illustrates an example of a magnetic alignment of portions of a resin. The resin included a main-chain liquid crystal elastomer formulation comprising RM82 mesogen/nba, $T_{NI} \sim 95$ °C. Part (a) illustrates a schematic drawing of the apparatus **700** for magnetic alignment. A layer **702** of resin was loaded between two glass plates **704**, and standalone neodymium magnet **706** was placed below a predefined portion **708** of the layer **702** of resin. A magnetic field was applied with the magnet **706** having a 0.5 Tesla magnetic field strength. It was noted that the 0.5 Tesla magnetic field strength is approximately half of the magnetic field used in studies for alignment of filler particles using a Fortify printer. The magnet **706** was placed underneath the glass slides and a UV light (large arrows) was exposed to the layers from the top slide to cure the layer **702** of resin between the glass plates **704**. The magnetic field was removed, The layer **702** after curing includes a cured portion **708** of aligned LCEs **710** and cured regions **712** of un-aligned LCEs **714**.

[0099] Part (b) of FIG. 7 is a polarized, optical microscope image of the magnetically aligned LCE. The dark regions of the image indicate random un-aligned LCEs **714** (illustrated as crosshatch region **712** of the layer **702** in part (a)) that were not exposed to a magnetic field during illumination of UV light. When viewed under a polarized optical microscope at 45°, with the analyzer (A) perpendicular to the polarizer (P), the bright regions of the image indicate aligned LCEs **710** (illustrated as diagonal line pattern of predefined portion **708** of the layer **702** in part (a)) cured during application of the magnetic field. The predefined alignment of LCEs demonstrated the use of magnetic field strength comparable to a Fortify printer to magnetically align a main-chain LCE resin for voxel-by-voxel alignment within 3D printed parts.

[00100] FIG. 8 depicts the characterization of the magneto-rheology of monomeric liquid crystal. The LCE resin included the prototypical nematic single crystal 4-cyano-4'-pentylbiphenyl (5CB, obtained from AmBeed, Inc., Arlington Heights, IL). The liquid crystal 5CB undergoes a phase transition from a crystalline state from a nematic state to an isotropic state at 35.0°C.

[00101] Part (a) illustrates the storage and loss modulus versus the strain amplitude of the 5CB resin. The liquid crystal 5CB behaves as a linear-viscoelastic material up to strain amplitudes of about 3000 %. Subsequent rheology measurements were therefore recorded at 300 %.

[00102] As shown in the plot of part (b), the magnetic field strength was varied to determine a critical magnetic field strength to align the LCs. The range of magnetic field strengths included 0.01 T, 0.05 T, 0.10 T, 0.50 T, and 1.00 T. Application of a magnetic field strength is represented as a B-field calculated as the magnetic flux through the sample during application of the magnetic field strength. Each respective magnetic field strength was applied to the resin up to 300 seconds at 50 °C, a temperature higher than the nematic-isotropic temperature of 5CB (35 °C). The critical magnetic field strength for aligning the LCs was determined to be about 100 mT (0.10 T) or greater (as measured at 100 seconds).

[00103] Part (c) includes a plot of storage modulus of the resin versus applied magnetic field strength (in terms of B-field). The resin demonstrated a deviation away from 1 (ratio G'_{on}/G'_{off} , storage modulus when magnetic field is present (on) and when no magnetic field is applied (off)) with the application of increasing magnetic field strength from about 0.10 T, thereby demonstrating alignment of LCs in the resin.

[00104] FIG. 9 depicts the characterization of the magneto-rheology of a liquid crystal oligomers having mechanical properties that are desirable for the applications described herein. The resin includes the LC oligomer LC RM82 with an n-butyl amine spacer (RM82-n-butyl amine). Part (a) illustrates the magnetic flux, B, calculated in Tesla of each applied magnetic field strength: 1.00 T (solid line), 0.10 T (●), and 0.05 T (□) over about 800 seconds. Starting at about 100 seconds, the magnetic flux is calculated in Tesla and corresponds to the applied magnetic field strength.

[00105] Part (b) illustrates the storage modulus of the resin at 50 °C for a duration of 800 seconds of each applied magnetic field strength. LC alignment effects were detected by an increase in storage modulus at an applied magnetic field strength of about 0.10 T (100 mT). The applied magnetic field strength of 0.05 T did not demonstrate a remarkable increase in storage modulus of the resin, and thus was below the critical magnetic field strength for LC alignment.

[00106] FIG. 10A depicts a series of polarized, optical microscope images of a resin after application of an in-plane magnetic field. Part (a) is an image of the in-plane alignment of the LC resin, and part (b) is the sample rotated 45° relative to the cross polarizers. The alignment of the LC molecules is visible by a change in brightness in a region when the sample is rotated. The dark regions shown in the image of part (a) are lighter in the image of the rotated sample of part (b). To visualize the changes in these

images, region **1** identified in part **(a)** and rotated in part **(b)** is represented by the different crosshatch patterns in the corresponding region **1** in the line drawings in parts **(c)** and **(d)**, respectively. Region **1** represents one portion of the cured LC resin of parts **(a)** and **(b)**.

[00107] FIG. 10B depicts a series of polarized, optical microscope images of a resin after application of a magnetic field that is out of the plane of the resin. Part **(a)** is an image of the out-of-plane alignment of the LC resin, and part **(b)** is the sample rotated 45° relative to the cross polarizers. The difference in the out-of-plane aligned LC molecules after rotation of the sample is less noticeable than the in-plane aligned LC molecules. The darker regions, representing the appearance of color in the original color image, signify that the LC molecules have an out-of-plane alignment being tilted with respect to the plane of the resin. To visualize the changes in these images, region **2** identified in parts **(a)** and rotated in part **(b)** is represented by different diagonal line patterns in the corresponding region **2** in the line drawings in parts **(c)** and **(d)**, respectively. Region **2** represents one portion of the cured LC resin of parts **(a)** and **(b)**.

[00108] FIG. 11 depicts tensile testing of the cured films illustrated in FIGS 10A and 10B. The film having in-plane alignment of LCs (●) having a stress/strain 1244 MPa is stiffer than the film having out-of-plane alignment of LCs (solid line) having a stress/strain of about 765 MPa. The in-plane alignment of the LCEs demonstrates an expected increase in moduli.

[00109] **In Use**

[00110] Various aspects described herein may be developed for reversible and repeatable 3D-to-3D shape change, adaptive optics, soft robotics, tunable stiffness, architectures, cellular fluidics, fluid filter, stimuli responsive behavior, etc. Various aspects described herein utilize liquid crystal elastomer alignment, 4D printing, responsive 3D structures, voxel-by-voxel shape change-directed printing, etc.

[00111] The inventive concepts disclosed herein have been presented by way of example to illustrate the myriad features thereof in a plurality of illustrative scenarios, aspects of an inventive concept, and/or implementations. It should be appreciated that the concepts generally disclosed are to be considered as modular, and may be implemented in any combination, permutation, or synthesis thereof. In addition, any modification, alteration, or equivalent of the presently disclosed features, functions, and concepts that

would be appreciated by a person having ordinary skill in the art upon reading the instant descriptions should also be considered within the scope of this disclosure.

[00112] While various aspects of an inventive concept have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of an aspect of an inventive concept of the present invention should not be limited by any of the above-described exemplary aspects of an inventive concept but should be defined only in accordance with the following claims and their equivalents.

CLAIMS

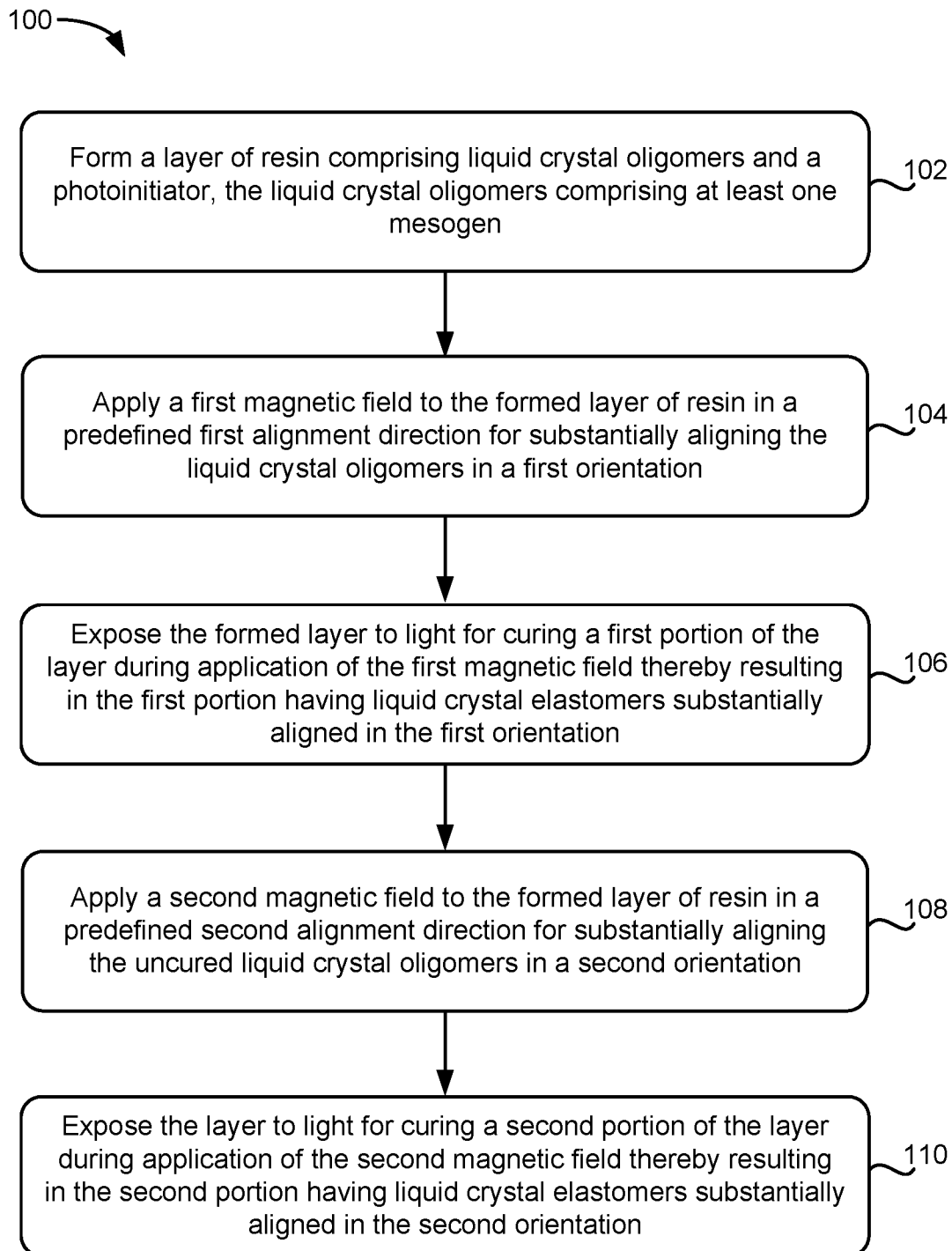
What is claimed is:

1. A method of forming a three-dimensional structure comprising liquid crystal elastomers, the method comprising:
forming a layer of resin comprising liquid crystal oligomers and a photoinitiator, the liquid crystal oligomers comprising at least one mesogen;
applying a first magnetic field to the formed layer of resin in a predefined first alignment direction for substantially aligning the liquid crystal oligomers in a first orientation;
exposing the formed layer to radiation for curing a first portion of the layer during application of the first magnetic field thereby resulting in the first portion having liquid crystal elastomers substantially aligned in the first orientation;
applying a second magnetic field to the formed layer of resin in a predefined second alignment direction for substantially aligning uncured liquid crystal oligomers in a second orientation; and
exposing the layer to radiation for curing a second portion of the layer during application of the second magnetic field thereby resulting in the second portion having liquid crystal elastomers substantially aligned in the second orientation.
2. The method as recited in claim 1, wherein the layer is formed using a lithography-based additive manufacturing system.
3. The method as recited in claim 1, comprising heating the resin to a temperature below the nematic-to-isotropic transition temperature of the at least one mesogen while forming the layer of resin.

4. The method as recited in claim 1, wherein the method does not include a heating step.
5. The method as recited in claim 1, wherein the predefined first alignment direction is different than the predefined second alignment direction.
6. The method as recited in claim 1, wherein each portion comprises at least one voxel.
7. The method as recited in claim 1, further comprising,
forming a second layer of resin adjacent to the layer of liquid crystal elastomers;
applying a third magnetic field to the formed second layer of resin in a third predefined alignment direction for aligning the liquid crystal oligomers in a third orientation; and
exposing the formed second layer to the radiation for curing a first portion of the second layer during application of the third magnetic field thereby resulting in the first portion of the formed second layer having liquid crystal elastomers substantially aligned in the third orientation.
8. The method as recited in claim 1, wherein an average aspect ratio of the at least one mesogen is about 3:1 to about 5:1.
9. The method as recited in claim 1, wherein exposing the formed layer to the radiation comprises projecting illumination from a digital light projector, wherein a light is projected on each predefined portion of aligned liquid crystal oligomers of the resin.
10. The method as recited in claim 1, wherein each portion is defined according to a respective mask applied to the formed layer during exposure of the layer to the radiation.

11. The method as recited in claim 1, wherein the resin includes an effective amount of an additive for assisting the alignment of the liquid crystal oligomers in a respective orientation.
12. The method as recited in claim 1, wherein a duration of time for substantially aligning the liquid crystal oligomers in one orientation according to the respective predefined alignment direction of the applied magnetic field is less than 10 seconds.
13. The method as recited in claim 1, wherein the resin includes a photoinhibitor.
14. The method as recited in claim 1, wherein the first and the second magnetic field have a magnetic field strength of at least 0.100 Tesla.
15. The method as recited in claim 1, wherein the resin includes an additive for increasing magnetic susceptibility of the liquid crystal oligomers.
16. A product, comprising:
a three-dimensional structure having a plurality of sequentially formed layers
comprised of liquid crystal elastomers,
wherein the liquid crystal elastomers in at least a predefined portion of a first
of the layers are substantially aligned in a first orientation,
wherein the liquid crystal elastomers in at least a predefined portion of a
second of the layers are substantially aligned in a second orientation,
wherein each of the portions of the three-dimensional structure is
characterized as exhibiting a shape change in response to a stimulus,
wherein the shape change is reversible.

17. The product as recited in claim 16, wherein the second orientation is the same as the first orientation, wherein the first orientation is different than an orientation of the as-deposited alignment of the liquid crystal elastomers.
18. The product as recited in claim 16, wherein the second orientation is different than the first orientation, wherein the first orientation is different than an orientation of the as-deposited alignment of the liquid crystal elastomers.
19. The product as recited in claim 16, wherein the liquid crystal elastomers in the first of the layers are substantially aligned in the first orientation.
20. The product as recited in claim 16, wherein at least 90 % of the liquid crystal elastomers in at least the predefined portion of the first of the layers are substantially aligned in the first orientation.
21. The product as recited in claim 16, wherein liquid crystal elastomers in a predefined second portion of the first of the layers are substantially aligned in an orientation that is different than the first orientation.
22. The product as recited in claim 16, wherein at least 90 % of the liquid crystal elastomers in the predefined second portion of the first of the layers are substantially aligned in the orientation that is different than the first orientation.
23. The product as recited in claim 16, wherein the liquid crystal elastomers in a predefined second portion of first layer are substantially aligned in an orientation different than the second orientation.

**FIG. 1**

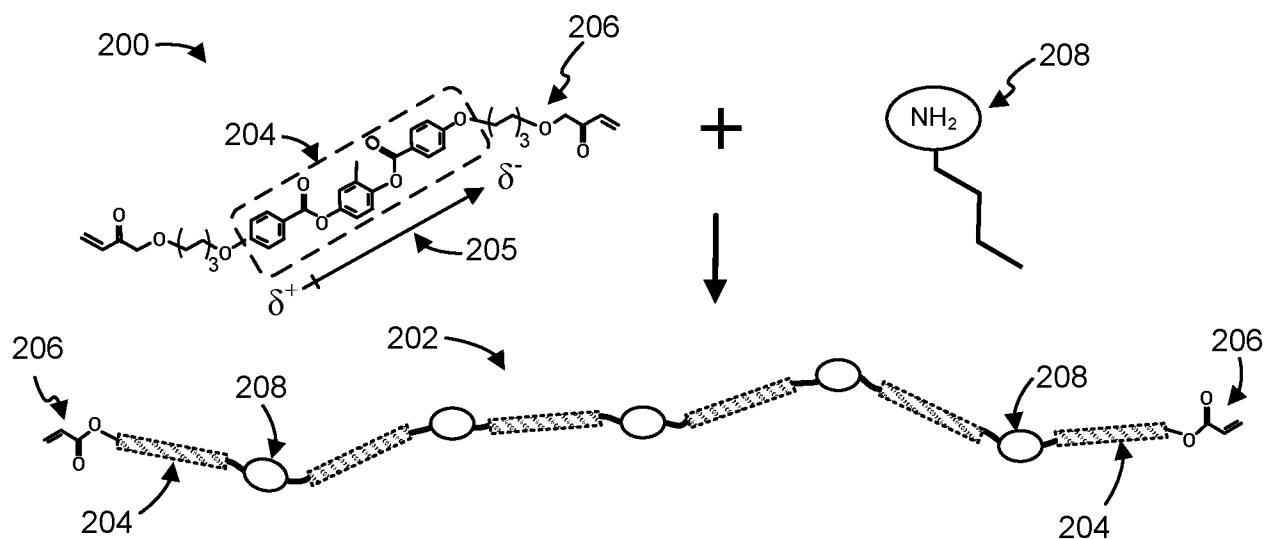


FIG. 2A

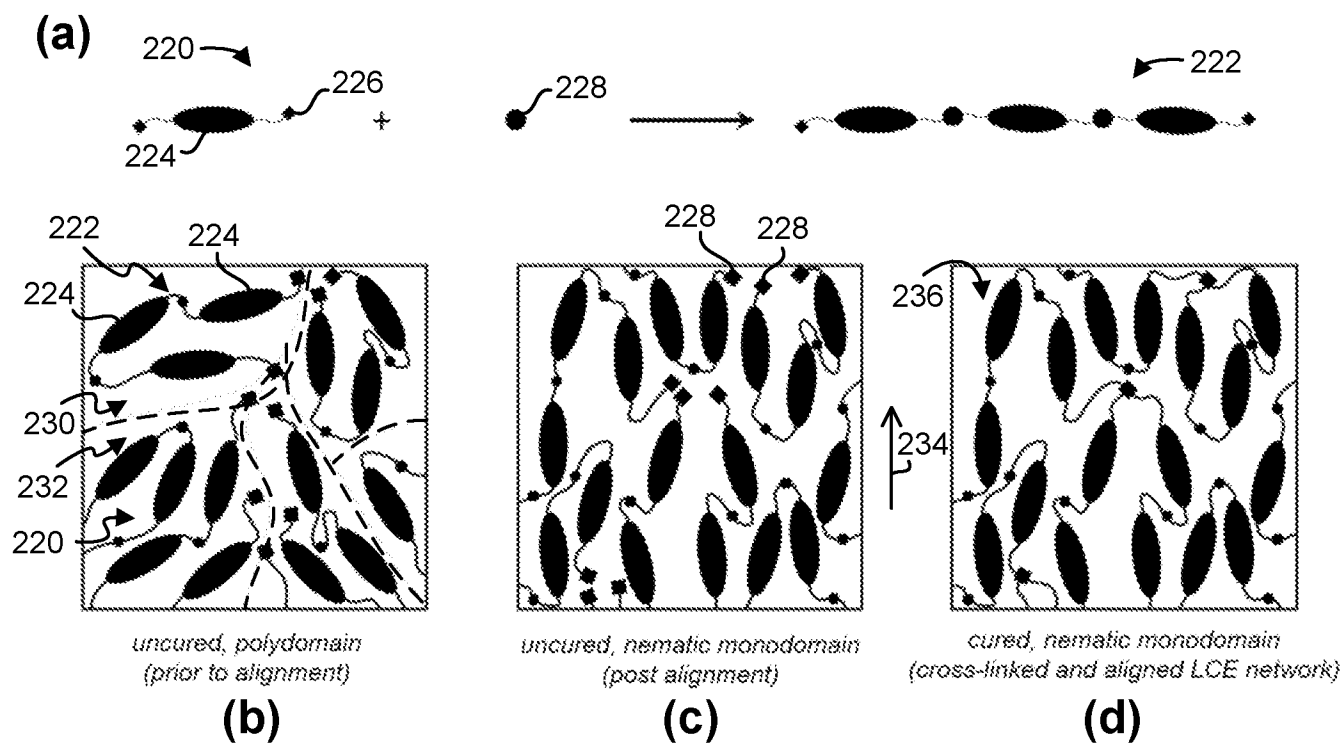


FIG. 2B

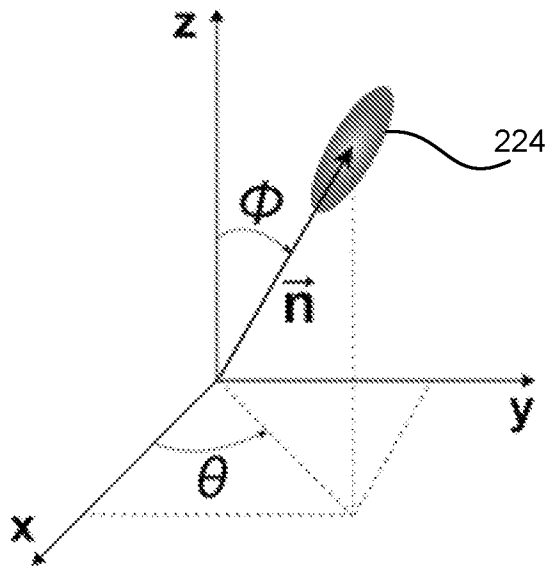


FIG. 2C

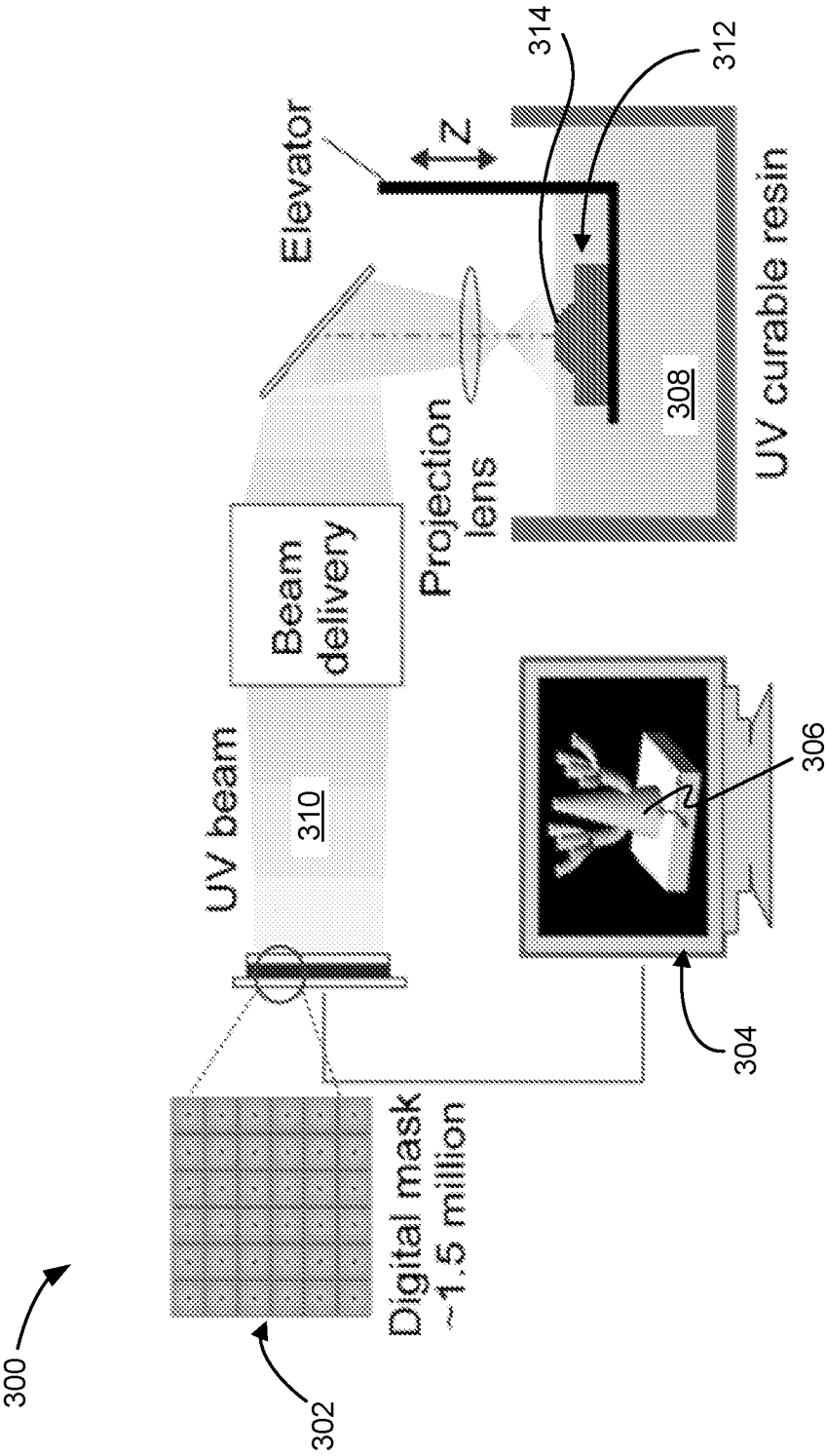


FIG. 3

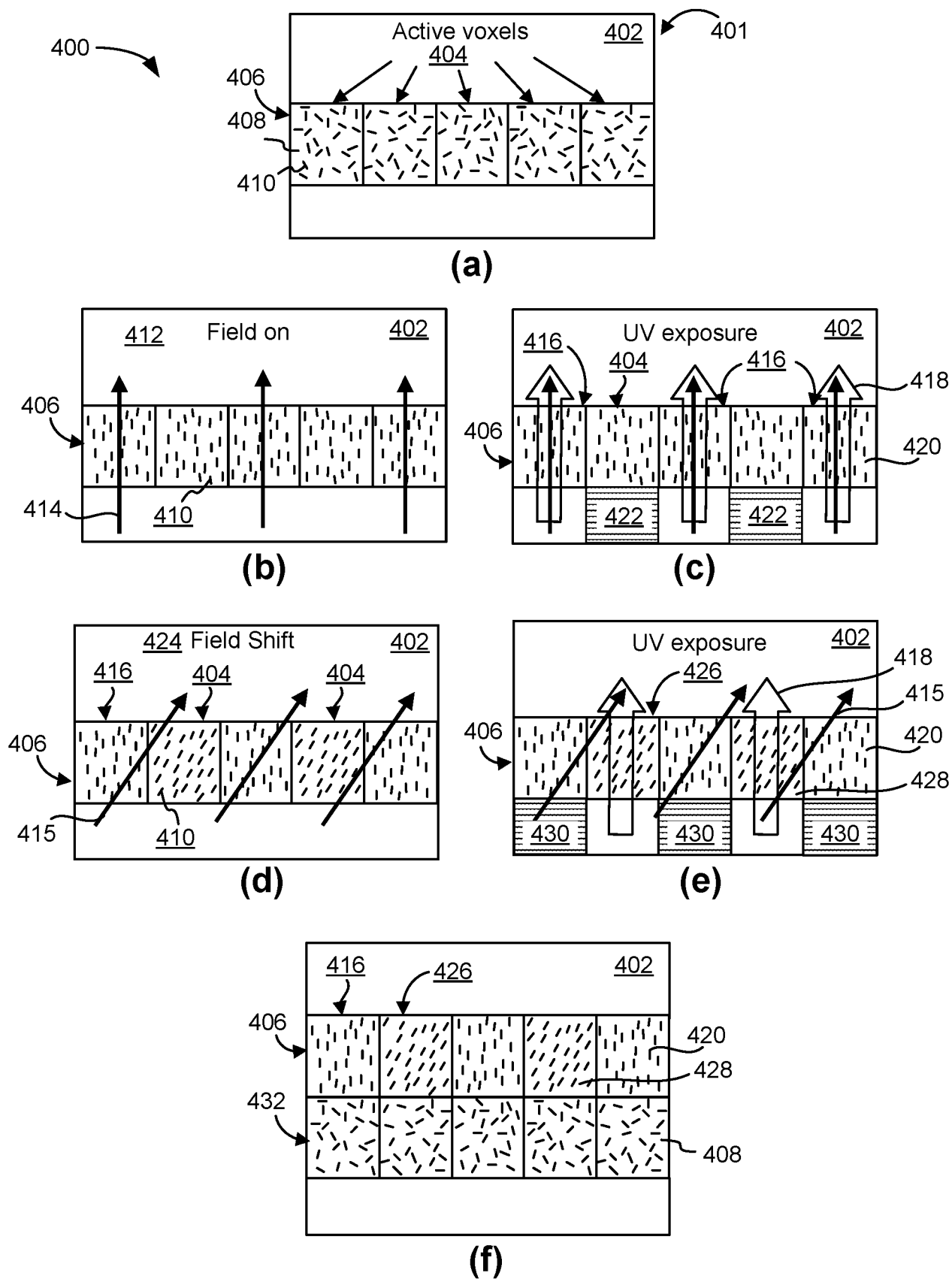


FIG. 4

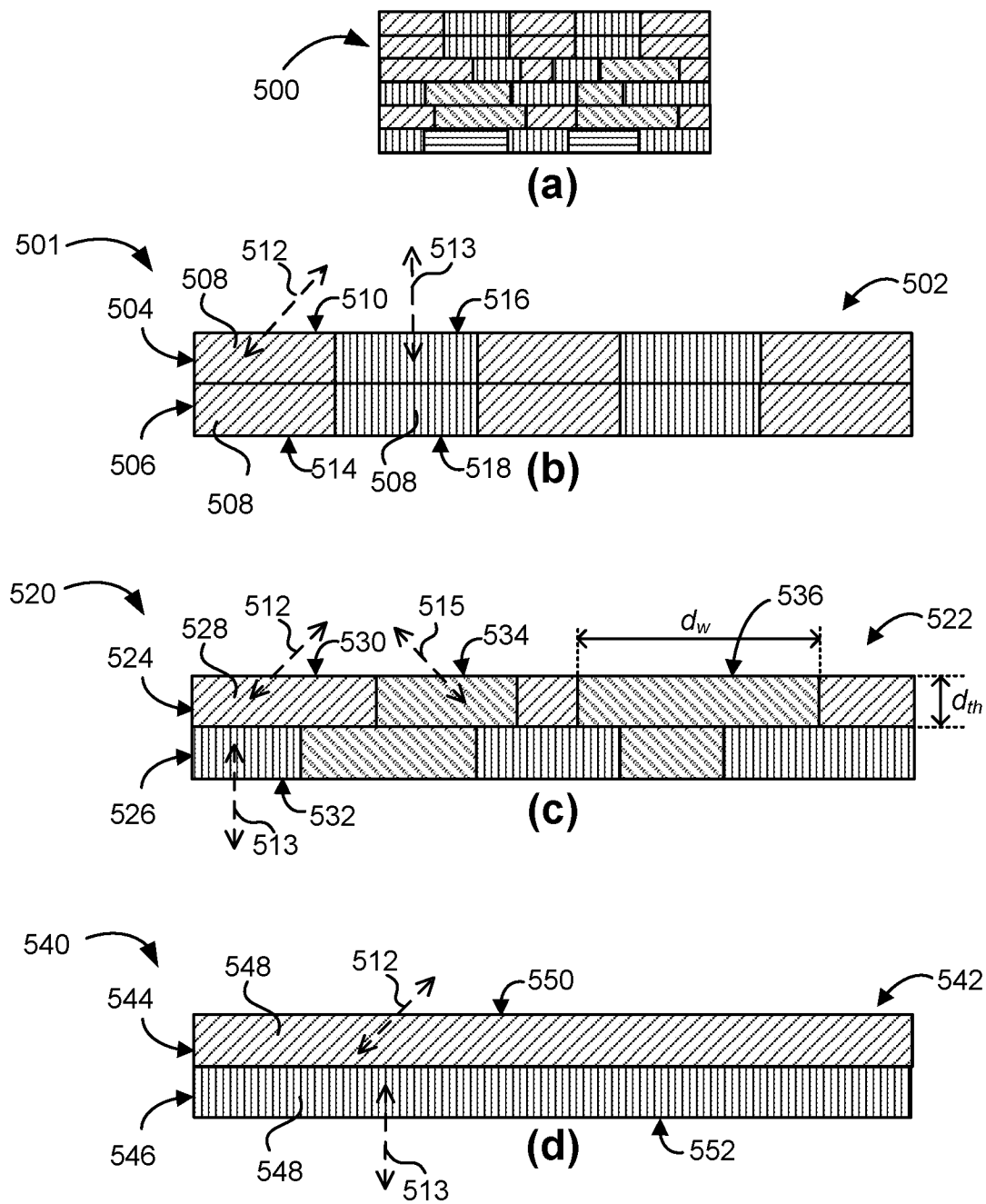


FIG. 5

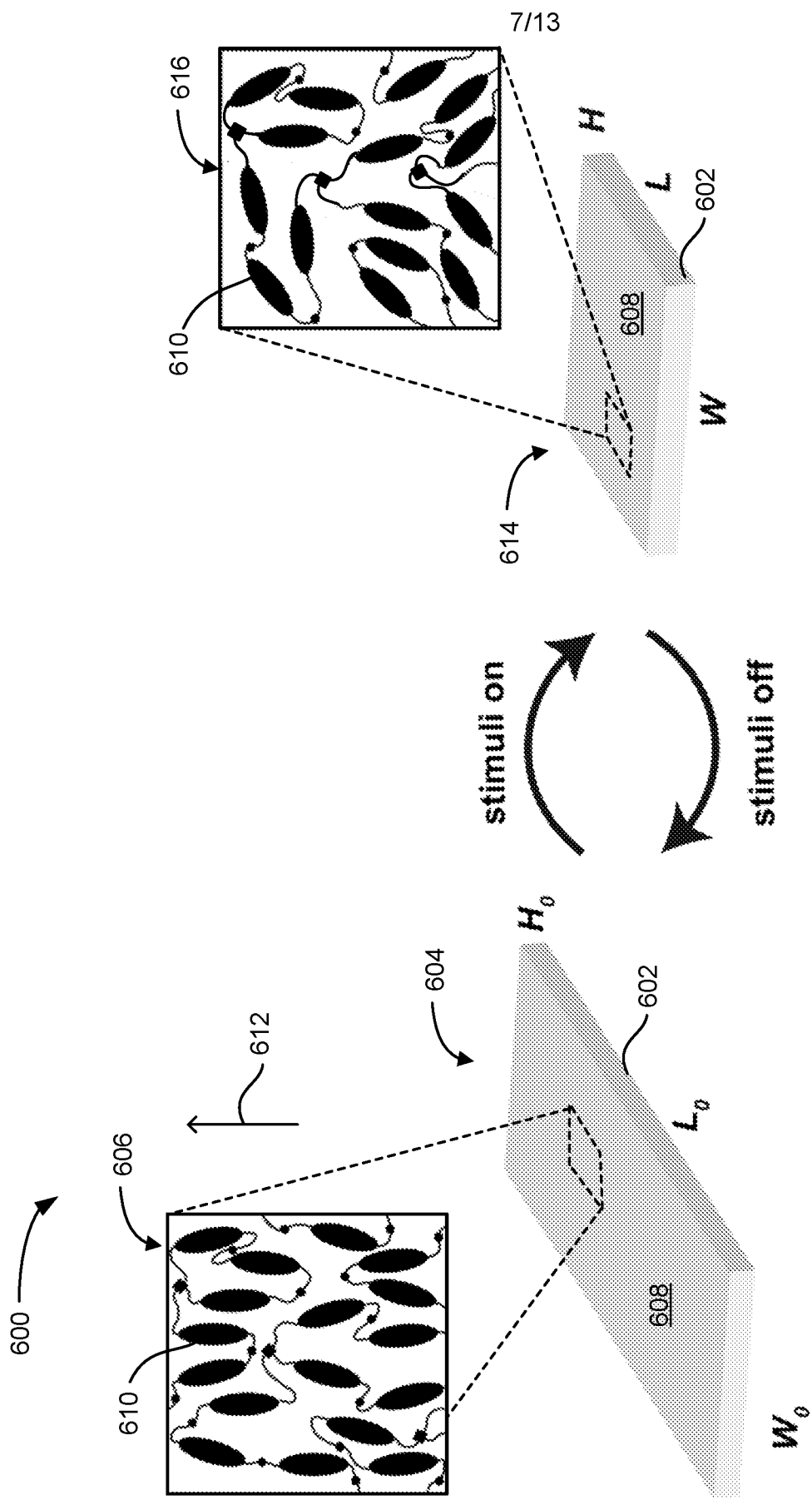


FIG. 6

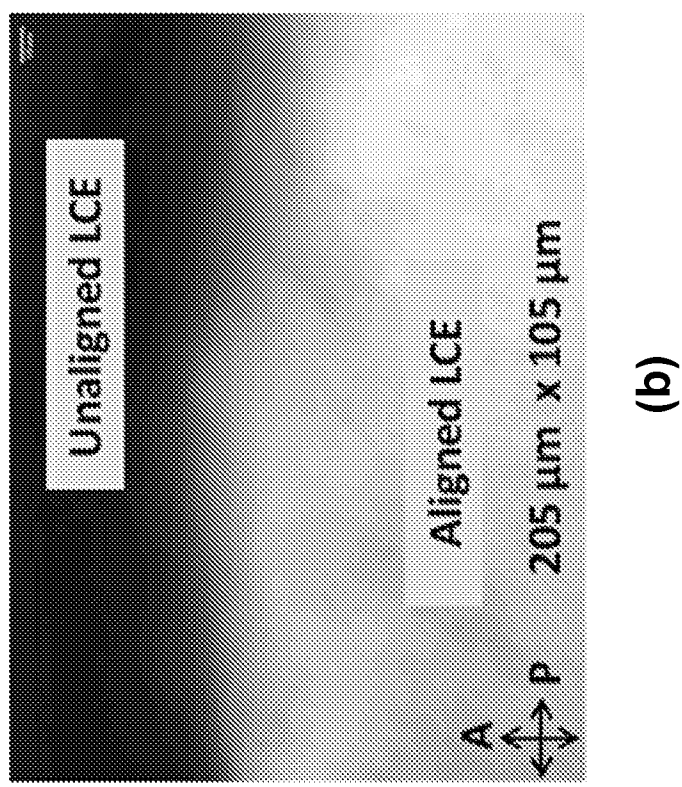
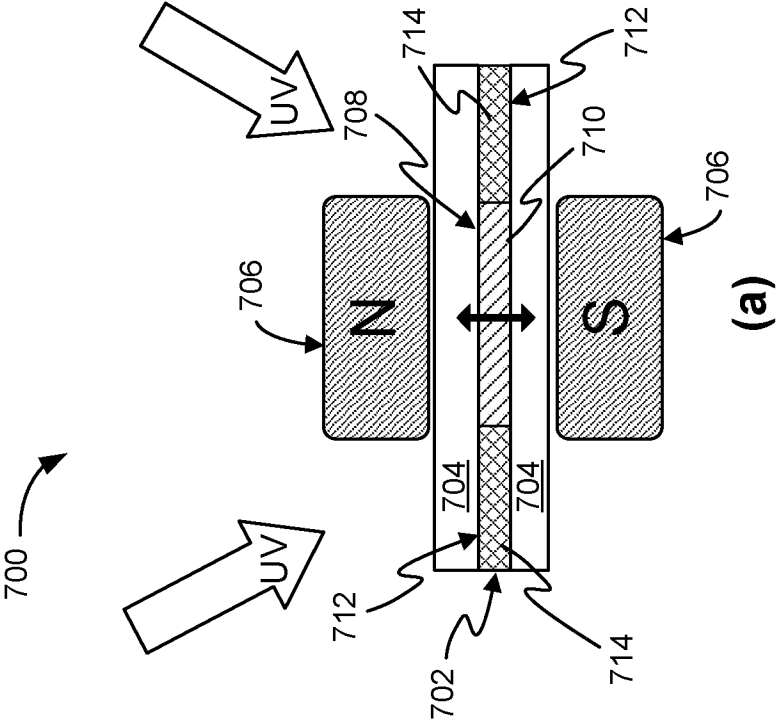


FIG. 7

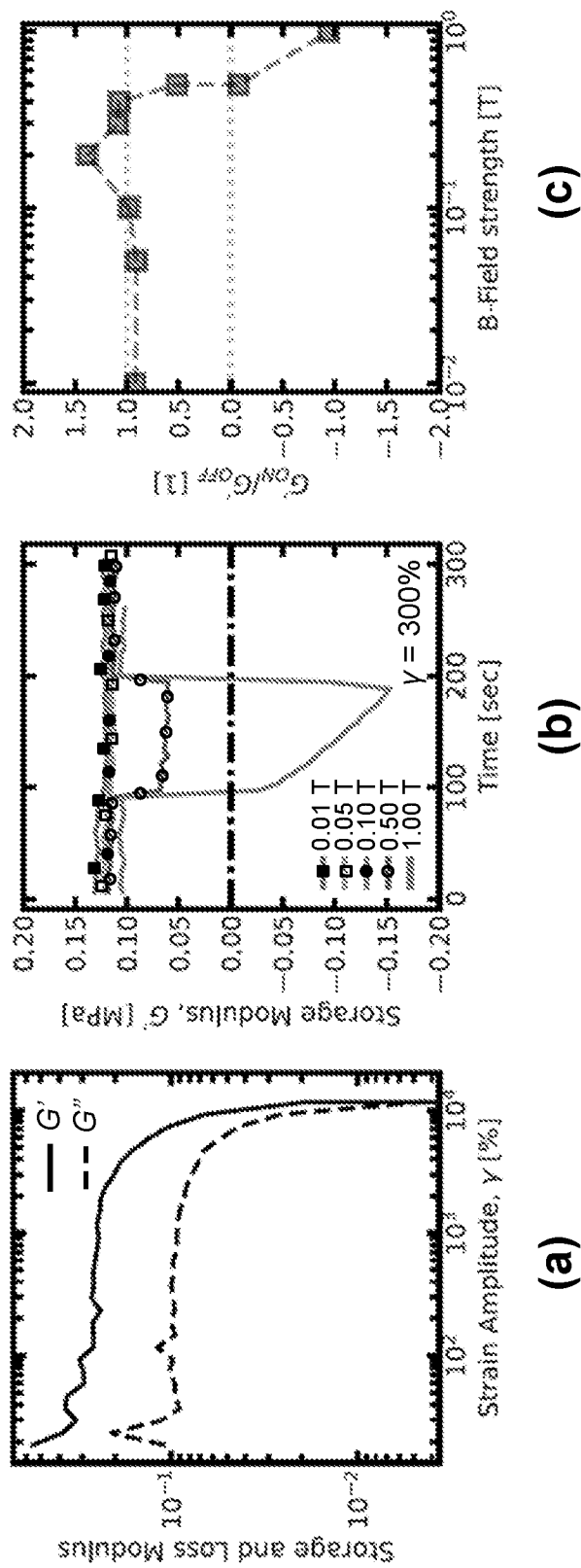


FIG. 8

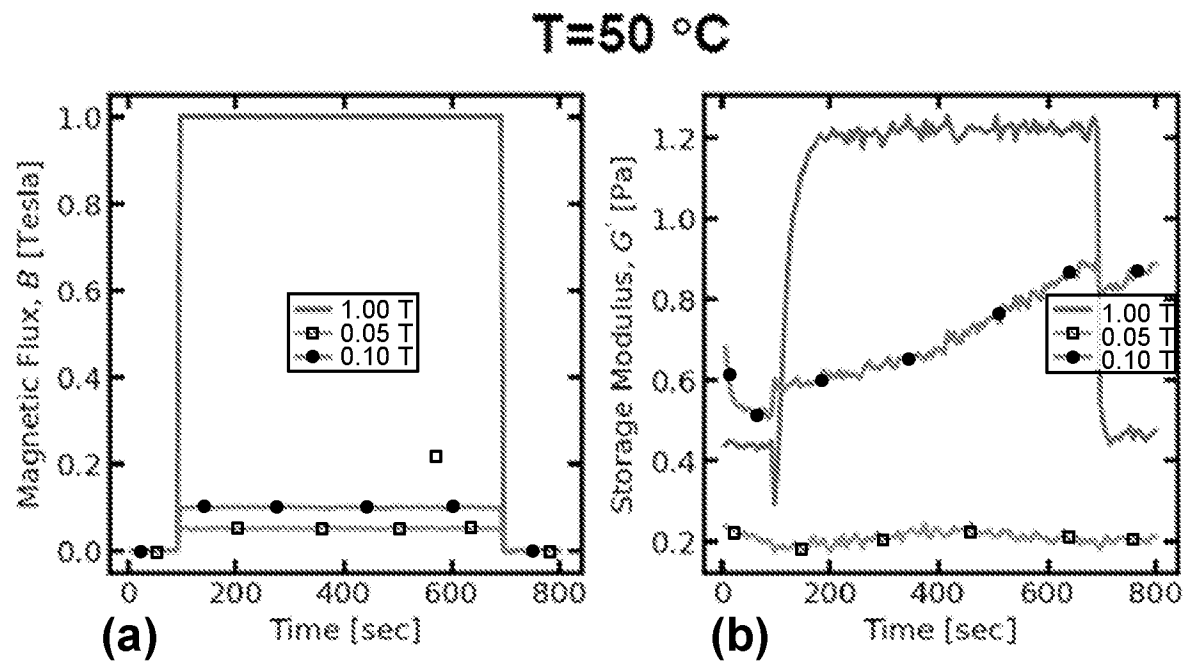
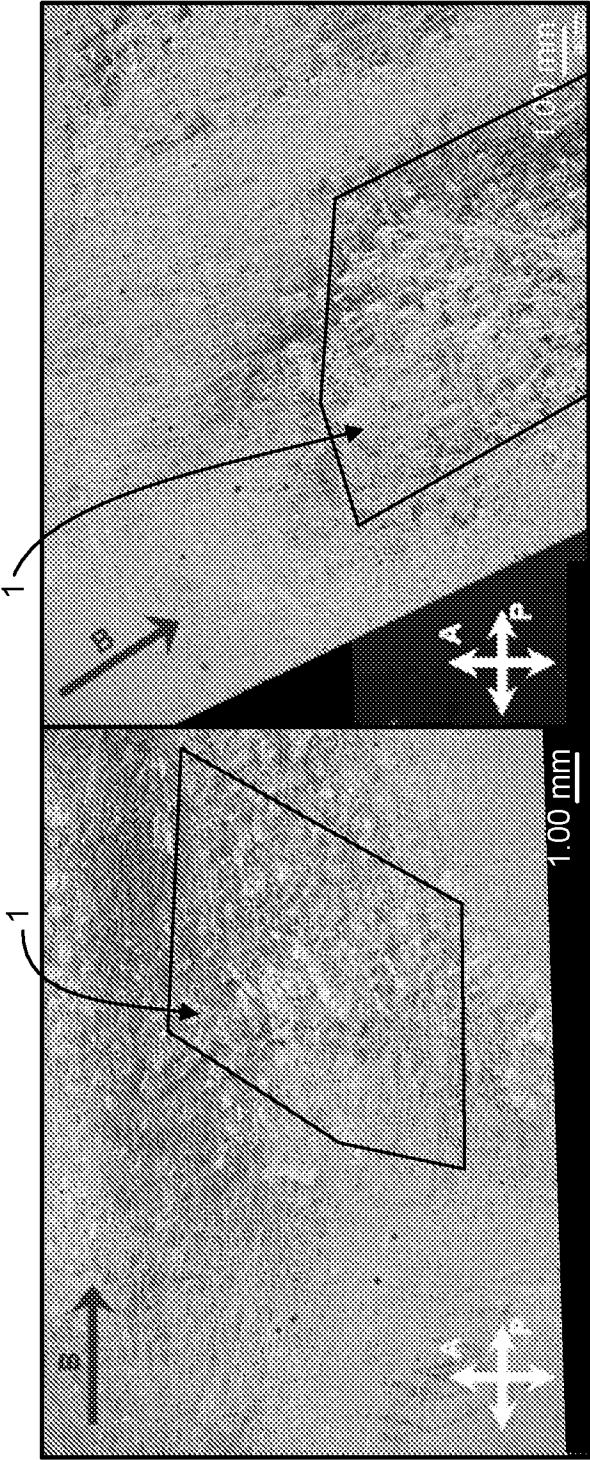


FIG. 9



In-plane alignment

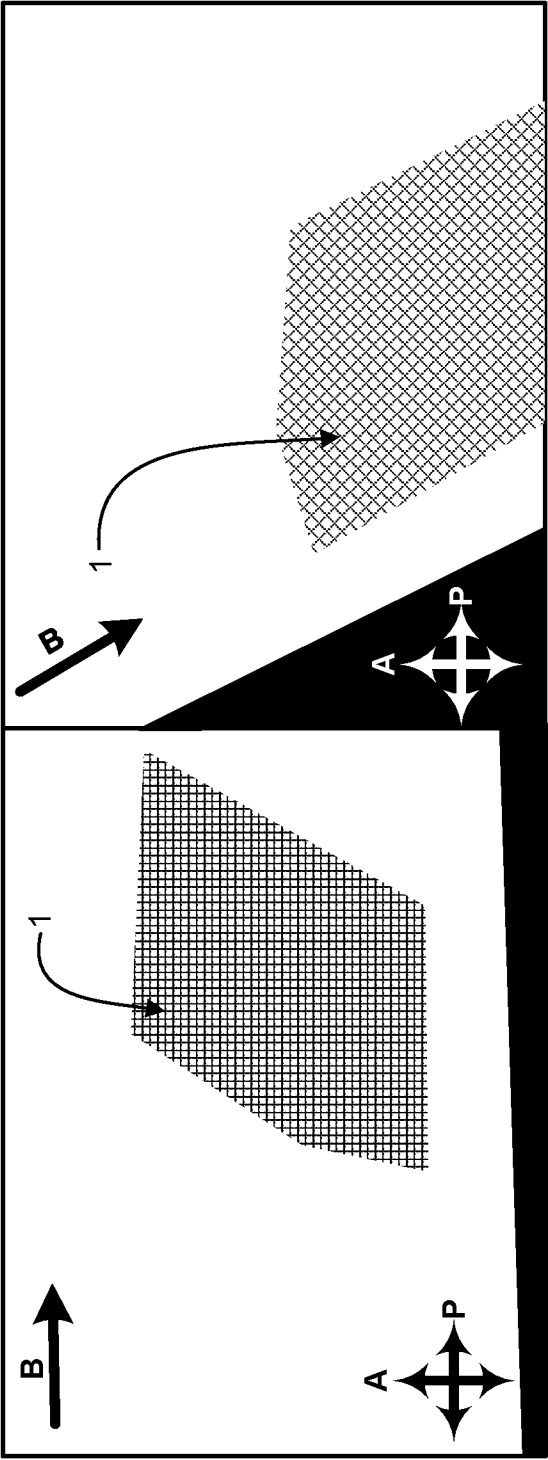


FIG. 10A

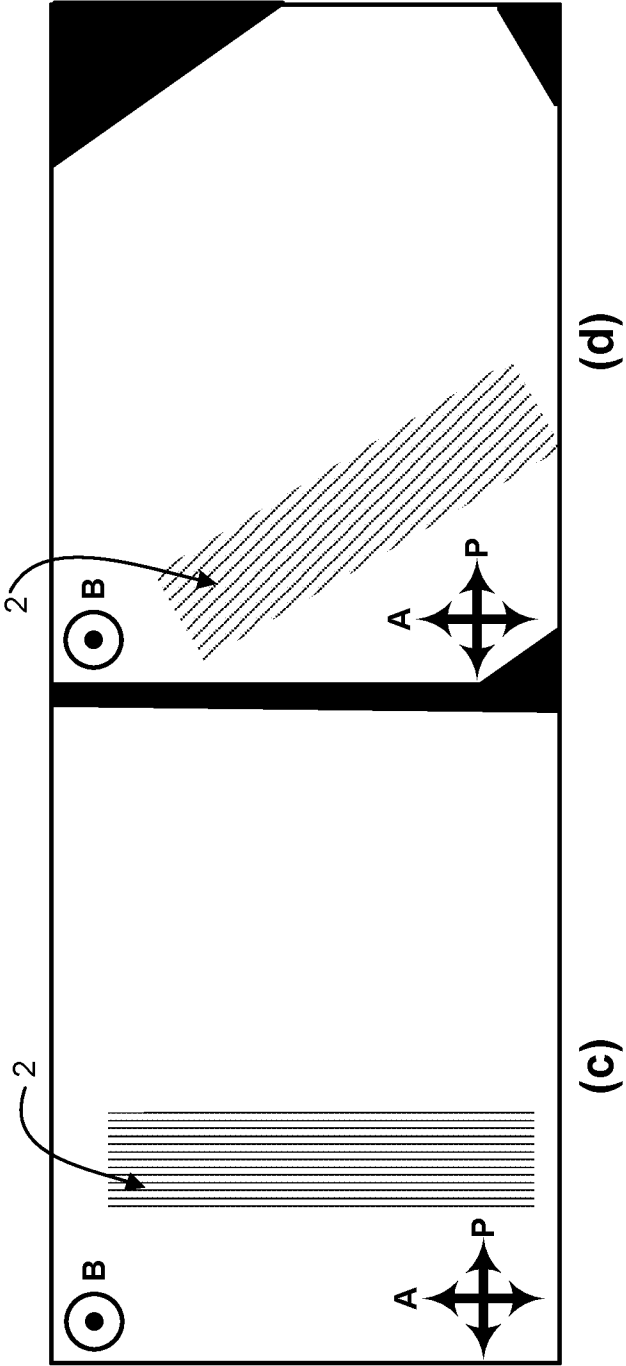
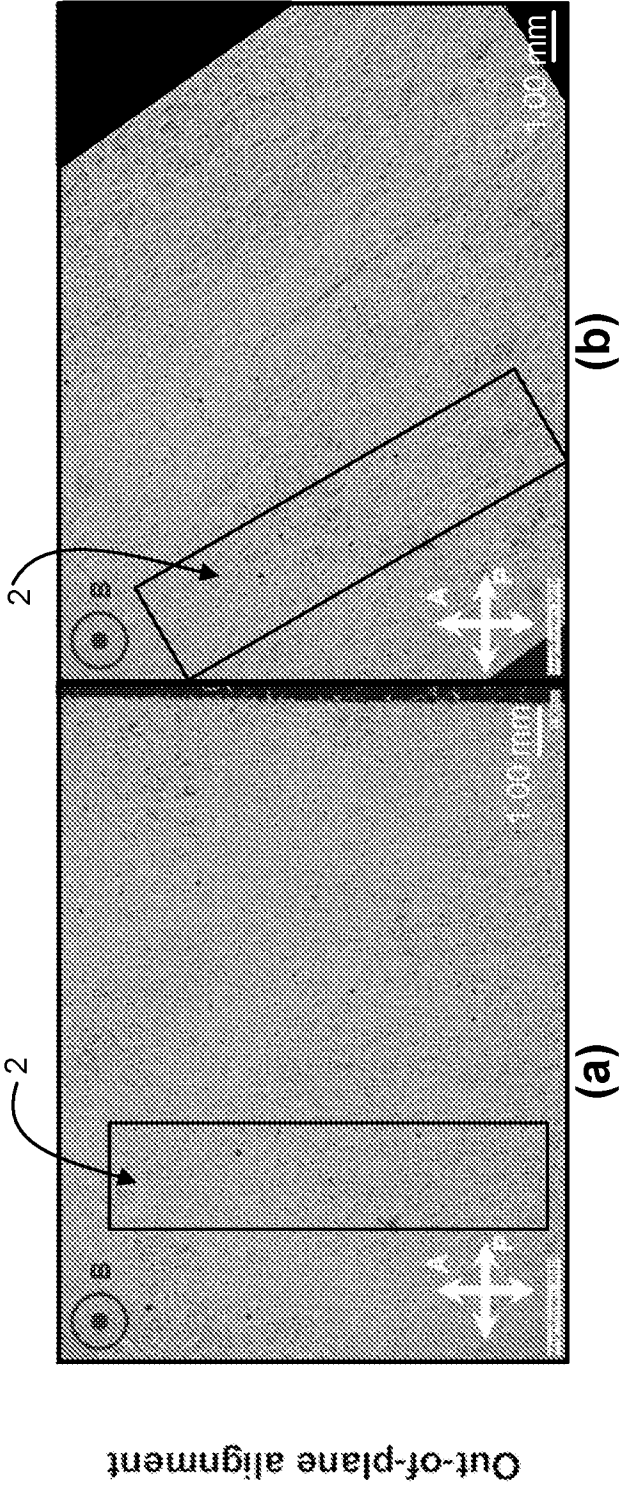
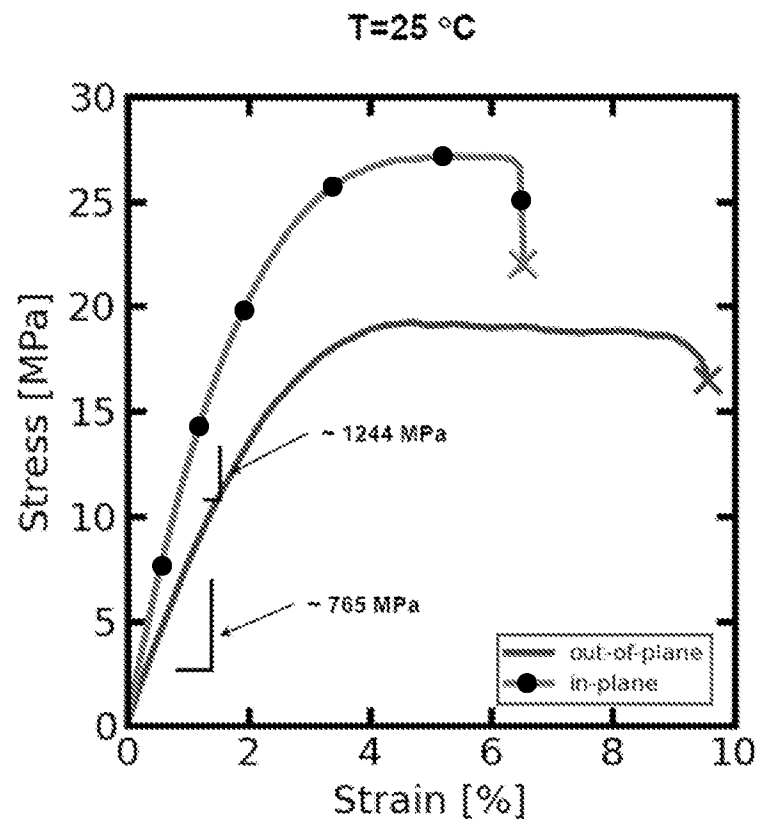


FIG. 10B

**FIG. 11**