



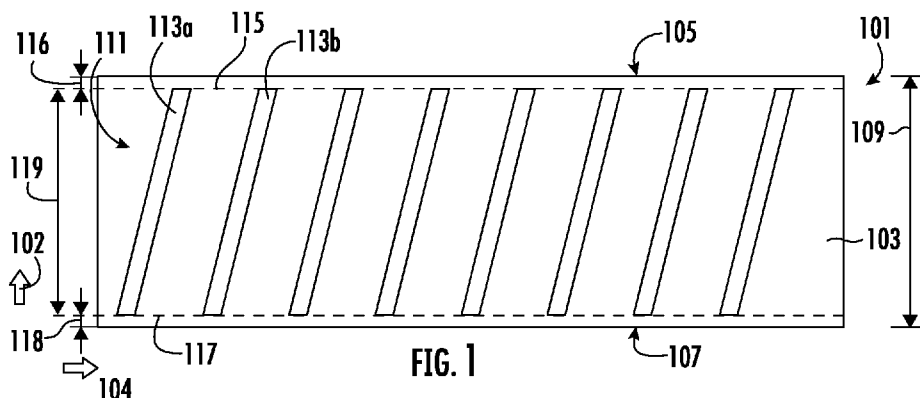
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- (54) **Title:** GLASS-CERAMIC ARTICLE AND METHOD OF FORMING A PLURALITY OF FEATURES THEREIN



- (57) **Abstract:** Glass-ceramic articles include a primary ceramic phase and an article thickness defined between a first major surface and a second major surface. Glass-ceramic articles include a plurality of features within an interior of the glass-ceramic article. The plurality of features include an amorphous glass phase. Methods of forming the plurality of features in the glass-ceramic article include emitting a burst of pulses from a laser that impinge the glass-ceramic article to form the plurality of features. In aspects, the burst of pulses melts a portion of a primary ceramic phase to form a feature comprising an amorphous glass phase within an interior of the glass-ceramic article.



GLASS-CERAMIC ARTICLE AND METHOD OF FORMING A PLURALITY OF FEATURES THEREIN

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 63/600,752 filed on November 20, 2023, the content of which is relied upon and incorporated herein by reference in its entirety.

FIELD

[0002] The present disclosure relates generally to a glass-ceramic article and a method of forming a plurality of features therein and, more particularly, to a glass-ceramic article comprising a plurality of features within an interior of the glass-ceramic article and methods of forming a plurality of features in a glass-ceramic article using a laser.

BACKGROUND

[0003] It is known to use an apparatus in display devices including liquid crystal displays (LCDs) and the like to light a display. It is known to use glass-ceramics for the housings of consumer electronic devices, including display devices. However, there is a need to improve the fracture toughness of glass-ceramics.

SUMMARY

[0004] The aspects of the disclosure can provide glass-ceramic articles including a plurality of features internal to the glass-ceramic article. As demonstrated by the Examples herein, the plurality of features interior to the glass-ceramic article increase a fracture toughness K_{IC} of the glass-ceramic article (e.g., relative to a glass-ceramic article without the plurality of features by 10% or more, from about 10% to about 35%, or from about 10% to about 20%). Without wishing to be bound by theory, it is believed that the plurality of features interior to the glass-ceramic article increases the fracture toughness K_{IC} by deflecting cracks and/or interrupting crack propagation within the glass-ceramic article. Also, a tilt angle of the features of the plurality of features can be controlled to further increase the fracture toughness.

[0005] Methods of the present disclosure can form the plurality of features interior to the glass-ceramic article by impinging a focused (e.g., line focus) laser beam (e.g.,

plurality of pulses) within the glass-ceramic article. The pulsed laser can quickly form the plurality of features. The shape and/or length of the features can be controlled by adjusting the beam shape, focusing optics, and other properties of an optical apparatus including the laser.

[0006] Aspect 1. A glass-ceramic article comprising:

a first major surface, a second major surface opposite the first major surface, and an article thickness defined therebetween;

a primary ceramic phase; and

a plurality of features within an interior of the glass-ceramic article, the plurality of features comprising an amorphous glass phase, a height in a direction of the article thickness.

[0007] Aspect 2. The glass-ceramic article of aspect 1, wherein a minimum distance between a feature of the plurality of features and the first major surface is in a range from about 10 micrometers to about 100 micrometers.

[0008] Aspect 3. The glass-ceramic article of any one of aspects 1-2, wherein a tilt angle relative to the direction of the article thickness of a feature of the plurality of features is in a range from about 0° to about 60°.

[0009] Aspect 4. The glass-ceramic article of aspect 3, wherein the tilt angle is in a range from about 30° to about 60°.

[0010] Aspect 5. The glass-ceramic article of aspect 3, wherein the tilt angle is in a range from about 0° to about 30°.

[0011] Aspect 6. The glass-ceramic article of any one of aspects 1-5, wherein a first set of features of the plurality of features are arranged in a line between the first major surface and the second major surface.

[0012] Aspect 7. The glass-ceramic article of aspect 6, wherein the height of a first feature in the first set of features is in a range from about 5 micrometers to about 500 micrometers.

[0013] Aspect 8. The glass-ceramic article of aspect 6, wherein the height of a first feature in the first set of features as a percentage of the article thickness is in a range from about 5% to about 30%.

[0014] Aspect 9. The glass-ceramic article of any one of aspects 1-5, wherein the height of the feature of the plurality of features as a percentage of the article thickness is in a range from about 50% to about 95%.

[0015] Aspect 10. The glass-ceramic article of any one of aspects 1-9, wherein each feature of the plurality of features extends along a corresponding axis, and a distance between the axes of an adjacent pair of features of the plurality of features is in a range from about 30 micrometers to about 300 micrometers.

[0016] Aspect 11. The glass-ceramic article of any one of aspects 1-5, wherein each feature of the plurality of features extends along a corresponding axis, and a first axis of a first feature of the plurality of features is colinear with a second axis of a second feature of the plurality of features.

[0017] Aspect 12. The glass-ceramic article of any one of aspects 10-11, wherein a width of a feature of the plurality of features perpendicular to the axis of the feature is in a range from about 500 nanometers to about 200 micrometers.

[0018] Aspect 13. The glass-ceramic article of aspect 12, wherein the width of the feature is in a range from about 10 micrometers to about 50 micrometers.

[0019] Aspect 14. The glass-ceramic article of any one of aspects 1-13, wherein a fracture toughness K_{IC} of the glass-ceramic article is about $1.9 \text{ MPa}\sqrt{\text{m}}$ or more.

[0020] Aspect 15. The glass-ceramic article of aspect 14, wherein the fracture toughness K_{IC} is in a range from about $1.95 \text{ MPa}\sqrt{\text{m}}$ to about $2.1 \text{ MPa}\sqrt{\text{m}}$.

[0021] Aspect 16. The glass-ceramic article of any one of aspects 1-13, wherein a fracture toughness K_{IC} of the glass-ceramic article is greater than a fracture toughness K_{IC} of another glass-ceramic article identical to the glass-ceramic article but without the plurality of features by about 5% or more.

[0022] Aspect 17. The glass-ceramic article of aspect 16, wherein the fracture toughness K_{IC} of the glass-ceramic article is greater than the fracture toughness K_{IC} of the another glass-ceramic article identical to the glass-ceramic article but without the plurality of features by from about 10% to about 20%.

[0023] Aspect 18. The glass-ceramic article of any one of aspects 1-17, wherein the primary ceramic phase comprises β -spodumene, β -quartz, nepheline, cordierite, spinel, lithium disilicate, or a combination thereof.

[0024] Aspect 19. The glass-ceramic article of any one of aspects 1-18, wherein a feature of the plurality of features is surrounded by the primary ceramic phase.

[0025] Aspect 20. The glass-ceramic article of any one of aspects 1-19, wherein the article thickness is in a range from about 100 micrometers to about 5 millimeters.

[0026] Aspect 21. A method of forming a plurality of features in a glass-ceramic article, the glass-ceramic article comprising a primary ceramic phase, a first major surface, a second major surface opposite the first major surface, and an article thickness defined between the first major surface and the second major surface, the method comprising:

adjusting a lens to create a line focus within the glass-ceramic article;

emitting a burst of pulses from a laser;

transmitting the burst of pulses through the lens; and

impinging the burst of pulses on the glass-ceramic article to form the plurality of features,

wherein the burst of pulses melts a portion of the primary ceramic phase to form a feature of the plurality of features comprising an amorphous glass phase, the plurality of features comprising a height in a direction of the article thickness, and the plurality of features are formed within an interior of the glass-ceramic article.

[0027] Aspect 22. The method of aspect 21, wherein a pulse of the burst of pulses comprising an energy in a range from about 1 microjoule to about 50 microjoules, and pulses of the burst of pulses are generated at a rate from about 50 kilohertz to about 1 megahertz.

[0028] Aspect 23. The method of any one of aspects 21-22, wherein an optical wavelength associated with the burst of pulses is in a range from about 300 nanometers to about 1500 nanometers.

[0029] Aspect 24. The method of aspect 23, wherein the optical wavelength is in a range from about 700 nanometers to about 1200 nanometers.

[0030] Aspect 25. The method of any one of aspects 21-24, wherein a pulse width of a pulse of the burst of pulses is in a range from about 500 femtoseconds to about 50 nanoseconds.

[0031] Aspect 26. The method of aspect 25, wherein the pulse width is in a range from about 1 picosecond to about 10 picoseconds.

[0032] Aspect 27. The method of any one of aspects 21-26, wherein a length of the line focus is in a range from about 10 micrometers to about 1 millimeter.

[0033] Aspect 28. The method of any one of aspects 21-24, wherein a shape of a pulse of the burst of pulses is Gaussian, Bessel, or Airy.

[0034] Aspect 29. The method of any one of aspects 21-28, further comprising impinging the burst of pulses on a spatial light modulator to generate a plurality of spatially distinct beam spots for each pulse of the burst of pulses, and impinging the plurality of spatially distinct beam spots on the generate a set of features of the plurality of features.

[0035] Aspect 30. The method of any one of aspects 21-29, wherein a minimum distance between a feature of the plurality of features and the first major surface is in a range from about 10 micrometers to about 100 micrometers.

[0036] Aspect 31. The method of any one of aspects 21-30, wherein a tilt angle relative to the direction of the height of a feature of the plurality of features is in a range from about 0° to about 60°.

[0037] Aspect 32. The method of aspect 31, wherein the tilt angle is in a range from about 30° to about 60°.

[0038] Aspect 33. The method of aspect 31, wherein the tilt angle is in a range from about 0° to about 30°.

[0039] Aspect 34. The method of any one of aspects 21-33, wherein a first set of features of the plurality of features are arranged in a line between the first major surface and a second major surface.

[0040] Aspect 35. The method of aspect 34, wherein the burst of pulses forms the first set of features.

[0041] Aspect 36. The method of any one of aspects 21-33, wherein each feature of the plurality of features extends along a corresponding axis, and a first axis of a first feature of the plurality of features is colinear with a second axis of a second feature of the plurality of features.

[0042] Aspect 37. The method of any one of aspects 34-35, wherein the height of a first feature in the first set of features is in a range from about 5 micrometers to about 500 micrometers.

[0043] Aspect 38. The method of any one of aspects 34-35, wherein the height of a first feature in the first set of features as a percentage of the article thickness is in a range from about 5% to about 30%.

[0044] Aspect 39. The method of any one of aspects 31-33, wherein the height of the feature of the plurality of features as a percentage of the article thickness is in a range from about 50% to about 95%.

[0045] Aspect 40. The method of any one of aspects 31-34, wherein each feature of the plurality of features extends along a corresponding axis, and a distance between the axes of an adjacent pair of features of the plurality of features is in a range from about 30 micrometers to about 300 micrometers.

[0046] Aspect 41. The method of aspect 35 or aspect 40, wherein a width of a feature of the plurality of features perpendicular to the axis of the feature is in a range from about 500 nanometers to about 200 micrometers.

[0047] Aspect 42. The method of aspect 41, wherein the width of the feature is in a range from about 10 micrometers to about 50 micrometers.

[0048] Aspect 43. The method of any one of aspects 31-42, wherein a fracture toughness K_{IC} of the glass-ceramic article is about $1.9 \text{ MPa}\sqrt{\text{m}}$ or more.

[0049] Aspect 44. The method of aspect 43, wherein the fracture toughness K_{IC} is in a range from about $1.95 \text{ MPa}\sqrt{\text{m}}$ to about $2.1 \text{ MPa}\sqrt{\text{m}}$.

[0050] Aspect 45. The method of any one of aspects 31-42, wherein a fracture toughness K_{IC} of the glass-ceramic article is greater than a fracture toughness K_{IC} of another glass-ceramic article identical to the glass-ceramic article but without the plurality of features by about 5% or more.

[0051] Aspect 46. The method of aspect 45, wherein the fracture toughness K_{IC} of the glass-ceramic article is greater than the fracture toughness K_{IC} of the another glass-ceramic article identical to the glass-ceramic article but without the plurality of features by from about 10% to about 20%.

[0052] Aspect 47. The method of any one of aspects 31-46, wherein the primary ceramic phase comprises β -spodumene, β -quartz, nepheline, cordierite, spinel, lithium disilicate, or a combination thereof.

[0053] Aspect 48. The method of any one of aspects 31-47, wherein a feature of the plurality of features is surrounded by the primary ceramic phase.

[0054] Aspect 49. The method of any one of aspects 31-48, wherein the article thickness is in a range from about 100 micrometers to about 5 millimeters.

BRIEF DESCRIPTION OF THE DRAWINGS

[0055] These and other features, aspects and advantages are better understood when the following detailed description is read with reference to the accompanying drawings, in which:

[0056] **FIG. 1** illustrates a cross-sectional side view of exemplary glass-ceramic article with a plurality of features according to aspects of the present disclosure;

[0057] **FIG. 2** illustrates a cross-sectional side view of another exemplary glass-ceramic article with a plurality of features according to aspects of the present disclosure;

[0058] **FIG. 3** is an enlarged view **3** of **FIG. 2** illustrating a set of features of the plurality of features;

[0059] **FIG. 4** illustrates a cross-section taken along the line **4-4** in **FIG. 3**;

[0060] **FIG. 5** illustrates an optical apparatus that can be used in a method of making a plurality of features in a glass-ceramic article;

[0061] **FIG. 6** is an enlarged view **6** of **FIG. 5** illustrating a line focus within the glass-ceramic article;

[0062] **FIG. 7** illustrates a configuration for determining fracture toughness K_{IC} in a double-cantilever beam method;

[0063] **FIG. 8** illustrates a cross-sectional view of a glass-ceramic article with a plurality of features having an amorphous glass phase from a scanning electron microscope (SEM);

[0064] **FIG. 9** is a top cross-sectional view of a glass-ceramic article in the configuration for the double-cantilever beam method;

[0065] **FIG. 10** illustrates a side of the glass-ceramic article with a plurality of laser lines and associated plurality of features in the configuration for the double-cantilever beam method;

[0066] **FIG. 11** illustrates a side of the glass-ceramic article with a plurality of laser lines and associated plurality of features at an inclination angle of 45° with crack deflection in the double-cantilever beam method;

[0067] **FIG. 12** illustrates a side of the glass-ceramic article with a plurality of laser lines and associated plurality of features at an inclination angle of 30° with crack deflection in the double-cantilever beam method;

[0068] **FIG. 13** illustrates a side of the glass-ceramic article with a plurality of laser lines and associated plurality of features at an inclination angle of 0° with crack deflection in the double-cantilever beam method;

[0069] **FIG. 14** illustrates a top cross-sectional view of the glass-ceramic article with crack deflection in the double-cantilever beam method; and

[0070] **FIG. 15** illustrates a cross-sectional view of the glass-ceramic article with the plurality of features having an amorphous glass phase with crack deflection in the double-cantilever beam method as imaged using a scanning electron microscope (SEM).

[0071] Throughout the disclosure, the drawings are used to emphasize certain aspects. As such, it should not be assumed that the relative size of different regions, portions, and substrates shown in the drawings are proportional to its actual relative size, unless explicitly indicated otherwise.

DETAILED DESCRIPTION

[0072] Aspects will now be described more fully hereinafter with reference to the accompanying drawings in which example aspects are shown. Whenever possible, the same reference numerals are used throughout the drawings to refer to the same or like parts.

[0073] **FIGS. 1-2** illustrate cross-sectional views of glass-ceramic articles **101** and **201** comprising a plurality of features **111** and **211** in accordance with aspects of the disclosure. Unless otherwise noted, a discussion of features of aspects of one planarization layer or coated article can apply equally to corresponding features of any aspects of the disclosure. For example, identical part numbers throughout the disclosure can indicate that, in some aspects, the identified features are identical to one another and that the discussion of the identified feature of one aspect, unless otherwise noted, can apply equally to the identified feature of any of the other aspects of the disclosure.

[0074] As shown in **FIGS. 1-2**, the glass-ceramic article **101 and 201** comprises a substrate **103** comprises a first major surface **105** and a second major surface **107** opposite the first major surface **105**. In aspects, the first major surface **105** can extend along a first plane, the second major surface **107** can extend along a second plane, and/or the second plane can be parallel to the first plane. As used herein, an article thickness **109** is defined between the first major surface **105** and the second major surface **107** as an average distance therebetween. In aspects, the article thickness **109** can be about 10 micrometers (μm) or more, about 25 μm or more, about 50 μm or more, about 75 μm or more, about 100 μm or more, about 125 μm or more, about 150 μm or more, about 200 μm or more, about 250 μm or more, about 300 μm or more, about 400 μm or more, about 500 μm or more, about 700 μm or more, about 1000 μm or more, about 5 millimeters (mm) or less, about 2 mm or less, about 1 mm or less, about 800 μm or less, about 600 μm or less, about 500 μm or less, about 300 μm or less, about 200 μm or less, about 150 μm or less, or about 100 μm or less. In aspects, the article thickness **109** can range from about 10 μm to about 5 mm, from about 25 μm to about 5 mm, from about 50 μm to about 5 mm, from about 75 μm to about 5 mm, from about 100 μm to about 5 mm, from about 125 μm to about 2 mm, from about 150 μm to about 1 mm, from about 200 μm to about 800 μm , from about 250 μm to about 600 μm , from about 300 μm 500 μm , from about 400 μm to about 500 μm , or any range or subrange therebetween. In aspects, although not shown, the article thickness **109** can be substantially constant along a significant amount of the substrate **103**, for example due to a substantially parallel arrangement of the first major surface **105** and the second major surfaces **107**. Alternatively, although not shown (e.g., rather than extending parallel to one another), the major surfaces may extend at an acute angle relative to one another, wherein a local distance therebetween can vary along a length and/or a width of the substrate **103**.

[0075] The substrate **103** can comprise primary ceramic phase. In aspects, the substrate **103** can be a ceramic-based material, for example, with the primary ceramic phase and an optional amorphous phase (not including the plurality of features **111 and 211** discussed herein). As used herein, “ceramic-based” includes both ceramics and glass-ceramics, wherein glass-ceramics have one or more crystalline phases and an amorphous, residual glass phase. Ceramic-based materials may be strengthened (e.g., chemically

strengthened). In aspects, a ceramic-based material can be formed by heating a glass-based material to form ceramic (e.g., crystalline) portions. In further aspects, ceramic-based materials may comprise one or more nucleating agents that can facilitate the formation of crystalline phase(s). In aspects, ceramic-based materials can comprise one or more oxides, nitrides, oxynitrides, carbides, borides, and/or silicides. Example aspects of ceramic oxides include zirconia (ZrO_2), zircon (ZrSiO_4), titania (TiO_2), hafnium oxide (Hf_2O), yttrium oxide (Y_2O_3), iron oxides, beryllium oxides, vanadium oxide (VO_2), fused quartz, cristobalite, mullite (a mineral comprising a combination of aluminum oxide and silicon dioxide), and spinel (MgAl_2O_4). Example aspects of ceramic nitrides include silicon nitride (Si_3N_4), aluminum nitride (AlN), gallium nitride (GaN), beryllium nitride (Be_3N_2), boron nitride (BN), tungsten nitride (WN), vanadium nitride, alkali earth metal nitrides (e.g., magnesium nitride (Mg_3N_2)), nickel nitride, and tantalum nitride. Example aspects of oxynitride ceramics include silicon oxynitride, aluminum oxynitride, and a SiAlON (a combination of alumina and silicon nitride and can have a chemical formula, for example, $\text{Si}_{12-m-n}\text{Al}_{m+n}\text{O}_n\text{N}_{16-n}$, $\text{Si}_{6-n}\text{Al}_n\text{O}_n\text{N}_{8-n}$, or $\text{Si}_{2-n}\text{Al}_n\text{O}_{1+n}\text{N}_{2-n}$, where m , n , and the resulting subscripts are all non-negative integers). In aspects, the primary ceramic phase of the substrate **103** can comprise β -spodumene, β -quartz, nepheline, cordierite, spinel, lithium disilicate, or a combination thereof.

[0076] In aspects, the glass-ceramic article can comprise a composition, based on 100 mol% of the glass-ceramic article of: from about 50 mol% to about 75 mol% SiO_2 , from about 55 mol to about 65 mol%, from about 59 mol% to about 64 mol%, from about 60 mol% to about 63 mol%), from about 1 mol% to about 5 mol% Al_2O_3 (e.g., from about 1.0 mol% to about 4 mol%, from about 1.0 mol% to about 3 mol%, from about 1.2 mol% to about 2.0 mol%), from about 10 mol% to about 40 mol% Li_2O (e.g., from about 15 mol% to about 35 mol%, from about 20 mol% to about 30 mol%, from about 22 mol% to about 27 mol%), from about 0 mol% to about 5 mol% Na_2O (e.g., from about 0.5 mol% to about 4 mol%, from about 1.0 mol to about 3 mol, from about 1.5 mol% to about 2.5 mol%), from about 0 mol% to about 5 mol% MgO (e.g., from about 0 mol% to about 3 mol%, from about 0 mol% to about 1 mol%, from about 0 mol% to about 0.5 mol%), from about 2 mol% to about 10 mol% CaO (e.g., from about 4 mol% to about 9 mol%, from about 5 mol% to about 8 mol%, from about 6 mol% to about 7 mol%), from about 0.1 mol

to about 3 mol% P_2O_5 (e.g., from about 0.5 mol% to about 2.5 mol%, from about 1.0 mol% to about 2.2 mol%, from about 1.5 mol% to about 2.0 mol%), and from about 0 mol% to about 5 mol% F^- (e.g., from about 0.1 mol% to about 4 mol%, from about 0.5 mol% to about 3, from about 1.0 mol% to about 2.0 mol%). In further aspects, the primary ceramic phase can be lithium disilicate. In even further aspects, the primary ceramic phase can comprise lithium disilicate as a primary ceramic phase and apatite (e.g., fluoroapatite) as a secondary phase.

[0077] In aspects, the substrate **103** can be optically transparent. As used herein, “optically transparent” or “optically clear” means an average transmittance of 70% or more in the wavelength range of 400 nm to 700 nm through a 1.0 mm thick piece of a material. In aspects, the substrate **103** may have an average transmittance of 75% or more, 80% or more, 85% or more, or 90% or more, 92% or more, 94% or more, 96% or more in the wavelength range of 400 nm to 700 nm through a 1.0 mm thick piece of the material. The average transmittance in the wavelength range of 400 nm to 700 nm is calculated by measuring the transmittance of whole number wavelengths from about 400 nm to about 700 nm and averaging the measurements.

[0078] With reference to **FIGS. 1-2**, the substrate **103** (e.g., glass-ceramic article **101 or 201**) comprises a plurality of features **111 or 211** internal to the substrate **103**. Throughout the disclosure, a feature is “internal” to a substrate or “within an interior” of the substrate if the feature does not comprise nor intersect a first major surface of the substrate, any major surface opposite the first major surface (e.g., second major surface), or any edge extending between the major surfaces. In aspects, the one or more (e.g., all) of the plurality of features **111 or 211** can be positioned within an interior of the substrate **103** (e.g., glass-ceramic article **101 or 201**). For example, with reference to **FIGS. 1-2**, the plurality of features **111 or 211** are within an interior of the substrate **103** because they do not comprise nor do they intersect the first major surface **105**, the second major surface **107** (shown as opposite the first major surface **105**), or any edge of the substrate. In further aspects, as shown in **FIGS. 1-3**, one or more (e.g., all) features of the plurality of features **111 or 211** can be separated from the first major surface **105** by a minimum distance **116 or 216** (i.e., between dashed line **115 or 215** and first major surface **105**) measured in a direction **102** of the article thickness **109** that is 10 μm or more, about 20 μm or more,

about 30 μm or more, about 40 μm or more, about 50 μm or more, about 100 μm or less, about 80 μm or less, about 60 μm or less, about 50 μm or less, about 40 μm or less, or about 30 μm or less. In further aspects, the minimum distance **116 or 216** that the one or more (e.g., all) features of the plurality of features **111 or 211** can be separated from the first major surface **105** measured in a direction **102** of the article thickness **109** can be in a range from about 10 μm to about 100 μm , from about 20 μm to about 80 μm , from about 30 μm to about 60 μm , from about 40 μm to about 50 μm , or any range or subrange therebetween. For example, in even further aspects, as shown in **FIG. 1**, all of the features of the features can be positioned a minimum distance **116** within one or more of the ranges discussed above in this paragraph. In further aspects, all of the plurality of features **111** (as shown in **FIG. 1**) or a set of the plurality of features **211** (e.g., features **214a** and **214d** shown in **FIG. 2**) can have a peripheral portion (e.g., see points **311a**, **315a**, and/or **315d** in **FIG. 3**) along the dashed line **115 or 215** (e.g., positioned substantially the same the minimum distance **116 or 216** from first major surface **105**). In further aspects, as shown in **FIGS. 1-2**, one or more features of the plurality of features **111 or 211** can be positioned a minimum distance **118 or 218** from the second major surface **107** (e.g., extending along dashed line **117 or 217**). In aspects, although not shown, the dashed line may impinge the peripheral portion at a single point depending on the shape of the feature.

[0079] In aspects, one or more features of the plurality of features **111 or 211** can comprise an amorphous glass phase. In further aspects, substantially all and/or all of the features of the plurality of features **111 or 211** can comprise an amorphous glass phase. In further aspects, the features (e.g., features **113a**, **113b**, and/or **214a-214f**) of the plurality of features **111 or 211** can be surrounded by the primary ceramic phase. For example, as discussed with reference to **FIG. 8**, the plurality of features (e.g., features **805a**, **805b**, **805c**, and/or **805d**) comprise an amorphous glass phase surrounded by a primary ceramic phase **801** of the substrate (e.g., glass-ceramic article). Without wishing to be bound by theory, as described below with reference to the method of making the ceramic-based article, it is believed that impinging the substrate with electromagnetic radiation (e.g., a burst of pulses of a laser) modify the primary ceramic phase by melting ceramic crystals at localized portions of the substrate within the interior of the substrate to form the amorphous

glass phase of features of the plurality of features surrounded by the primary ceramic phase (e.g., largely undisturbed outside of the features).

[0080] The feature **214a** will be described below with the understanding that the description can equally apply to the features **113a-113b and/or 214b-214f** of the plurality of features **111 and/or 211**. In aspects, as shown in **FIG. 3**, the feature **214a** comprises a plurality of points **311a, 313a, 315a, and 317a** defining a periphery (i.e., outer periphery) of the feature **214**. Similarly, feature **214b** can comprise points **311b, 313b, 315b, and 317b** on the periphery, feature **214d** can comprise points **315d and 317d** on the periphery, and/or feature **214e** can comprise points **315e and 317e** on the periphery. Although, the points define a rectangular cross-section, it is to be understood that the cross-section can be polygonal, curved, and/or curvilinear, for example, oval-shaped and/or tear-drop-shaped. As used herein, a “height” or “feature height” of a feature is defined as a maximum distance, measured as a component in the direction of the article thickness, of a path extending between points on the periphery of the corresponding feature that is entirely within the feature (excluding any incidental portion at the end-points). For example, as shown in **FIG. 2-3**, the feature height **212** of feature **214a** is a component in the direction **102** of the article thickness **109** (see **FIG. 2**) of a path extending between points (e.g., point **311a** and point **313a or 317a**, point **315a** and point **313a or 317a**) on the periphery of the feature **214a** that is entirely within the feature (other than any incidental portion at the end points) the maximizes the feature height **212**.

[0081] In aspects, the feature height **119 and/or 212** can be about 5 μm or more, about 10 μm or more, about 20 μm or more, about 30 μm or more, about 50 μm or more, about 70 μm or more, about 100 μm or more, about 500 μm or less, about 400 μm or less, about 300 μm or less, about 250 μm or less, about 200 μm or less, about 150 μm or less, about 100 μm or less, about 80 μm or less, or about 50 μm or less. In aspects, the feature height **119 and/or 212** can be in a range from about 5 μm to about 500 μm , from about 10 μm to about 400 μm , from about 20 μm to about 300 μm , from about 30 μm to about 250 μm , from about 40 μm to about 200 μm , from about 50 μm to about 150 μm , from about 70 μm to about 100 μm , or any range or subrange therebetween. Alternatively or additionally, for example with reference to features (e.g., features **113a-113b**) of the plurality of features **111** shown in **FIG. 1**, the feature height **119** as a percentage of the

article thickness **109** can be about 50% or more, about 60% or more, about 70% or more, about 75% or more, about 80% or more, about 85% or more, about 95% or less, about 90% or less, about 85% or less, about 80% or less, about 75% or less, about 70% or less, or about 60% or less. For example, with reference to features (e.g., features **113a-113b**) of the plurality of features **111** shown in **FIG. 1**, the feature height **119** as a percentage of the article thickness **109** can be in a range from about 50% to about 95%, from about 60% to about 90%, from about 65% to about 85%, from about 70% to about 80%, from about 75% to about 80%, or any range or subrange therebetween. For example, feature **113a** can extend for a majority of the article thickness (e.g., feature height **119** is 50% or more of the article thickness **109**), and/or substantially all of the features **113a-113b** of the plurality of features **111** can comprise a feature height within one or more of the ranges discussed above for the feature height **119**. Alternatively, feature **214a** can extend for less than a majority of the article thickness and/or be aligned in a line (e.g., axis **301**, **316a**, and/or **316a**) with other features (e.g., features **214b** and/or **214c**) between the first major surface **105** and the second major surface **107**. Alternatively or additionally, for example with reference to features (e.g., features **214-214f**) of the plurality of features **211** shown in **FIG. 2**, the feature height **212** as a percentage of the article thickness **109** can be about 5% or more, about 8% or more, about 10% or more, about 12% or more, about 15% or more, about 20% or more, about 35% or less, about 30% or less, about 25% or less, about 20% or less, about 15% or less, or about 10% or less. For example, with reference to features (e.g., features **214a-214f**) of the plurality of features **211** shown in **FIG. 2**, the feature height **212** as a percentage of the article thickness **109** can be in a range from about 5% to about 35%, from about 8% to about 35%, from about 10% to about 35%, from about 10% to about 30%, from about 10% to about 20%, from about 15% to about 20%, or any range or subrange therebetween. In aspects, the substantially all or all of the features of the plurality of features can comprise the same feature height, for example, within one or more of the ranges discussed above with reference to the feature height **119** and/or **212**.

[0082] In aspects, as shown in **FIGS. 3-4**, a feature **214e** can extend along an axis **316c**. As shown in **FIG. 3**, the axis **316c** of feature **214e** can extend parallel to (and/or co-linear with) a path between points on the periphery of the feature **214e** (e.g., path between point **315e** and **317e**). The axis **316c** can be a central axis of the feature **214e**. The axis

316c can extend through a centroid of the cross-section shown in **FIG. 4** (taken along line **4-4** in **FIG. 3**) and/or extend through the centroid of a plurality of cross-sections (e.g., all cross-sections) of the feature taken perpendicular to the axis. For example, as shown in **FIG. 3**, feature **214a** extends along axis **316a**, feature **214b** extends along axis **316b**, and feature **214d** extends along axis **316d**. In aspects, as shown in **FIG. 3**, the axes **316a** and **316b** of a set of features (i.e., features **214a** and **214b**) can be parallel and/or colinear. In aspects, as shown in **FIG. 3**, a set of features (e.g., features **214a** and **214b**) can extend along a common axis **301**, which can be colinear with or identical to the axis **316a** and/or **316b** that the individual features **214a** and **216b** extend along. Consequently, the set of features (e.g., features **214a**, **214b**, and **214c** shown in **FIG. 2**) can be arranged in a line **213a** extending between the first major surface **105** and the second major surface. In further aspects, the plurality of features (e.g., features **214a-214f**) can comprise a plurality of sets of features with the features in each set of features arranged in a line. In even further aspects, the lines associated with the plurality of sets of features can be substantially parallel and/or parallel to an adjacent line and/or all of the lines. Similarly, features **214d** and **214e** can extend along axes **316c** and/or **316d** that are colinear with and/or identical to axis **303** and/or arranged in a line **213b** between the first major surface **105** and the second major surface (see **FIG. 2**).

[0083] Throughout the disclosure, a “tilt angle” is defined as an angle between 0° and 90° formed between the axis that the feature extends along and a direction of the article thickness. For example, as shown in **FIG. 3**, the tilt angle **321** of feature **214a** is defined as an angle formed between the axis **316a** that the feature **214a** extends along and a direction **102** of the article thickness **109** (see **FIGS. 1-2**) (e.g., a direction normal to the first major surface **105** and the second major surface **107** when the major surfaces are parallel to another). In aspects, as shown in **FIG. 3**, the tilt angle **321** of axes **301**, **316a**, and/or **316b** of the features **214a** and/or **214b** of the plurality of features **211** and/or the corresponding line **213a** can be about 0° or more, about 5° or more, about 10° or more, about 15° or more, about 20° or more, about 25° or more, about 30° or more, about 35° or more, about 40° or more, about 45° or more about 50° or more, about 55° or more, about 60° or less, about 55° or less, about 50° or less, about 45° or less, about 40° or less, about 35° or less, about 30° or less, about 25° or less, about 20° or less, about 15° or less, or about 10° or less. In

aspects, the tilt angle **321** of axes of the features of the plurality of features and/or corresponding line can be in a range from about 0° to about 60°, from about 5° to about 55°, from about 10° to about 50°, from about 15° to about 45°, from about 20° to about 40°, from about 25° to about 35°, from about 25° to about 30°, or any range or subrange therebetween. In aspects, the tilt angle **321** of axes of the features of the plurality of features and/or corresponding line can be about 30° or more, for example in a range from about 30° to about 60°, from about 35° to about 55°, from about 40° to about 50°, from about 40° to about 45°, or any range or subrange therebetween. In aspects, the tilt angle **321** of axes of the features of the plurality of features and/or corresponding line can be about 30° or less, for example in a range from about 0° to about 30°, from about 5° to about 25°, from about 10° to about 20°, from about 15° to about 20°, or any range or subrange therebetween. It is to understand that the ranges discussed in this paragraph for the tilt angle can apply to any and/or all feature(s) of the plurality of features, lines of features, and/or axes of features of the plurality of features. In aspects, as shown in **FIGS. 1-2**, substantially all and/or all of the features of the plurality of features can comprise substantially the same (e.g., same) tilt angle. Alternatively, although not shown, one or more features of the plurality of features can have a different tilt angle than a tilt angle of another feature of the plurality of features.

[0084] Generally, referring to the cross-section taken along the line **4-4** in **FIG. 3** shown in **FIG. 4**, a shape of the cross-section of the feature **214e** (i.e., the shape of a cross-section perpendicular to the axis) can be curved (e.g., circular, ellipsoidal shape), polygonal, curvilinear, or combinations thereof. In aspects, as shown in **FIG. 4**, the shape of the feature is ellipsoidal. In further aspects, although not shown, the shape of a set of features and/or all of the features of the plurality of features can comprise substantially the same and/or the same shape perpendicular to the corresponding axis. Alternatively, one or more features of the plurality of features can comprise a different shape perpendicular to the corresponding axis than a corresponding shape of another feature.

[0085] Throughout the disclosure, a width of a feature is defined as a maximum component of a distance between points on the periphery of the feature in a plane perpendicular to the axis that the feature extends along, where a path connecting the points is entirely within the feature (other than any incidental portion at the endpoints). For example, with reference to **FIG. 4**, the width **309** of the feature **214e** is the maximum

component of a distance between points **407 and 409** on the periphery of the feature **214e**, wherein the points **407 and 409** lie in a plane perpendicular to the axis **316e** that the feature extends along, a path connecting the points **407 and 409** is entirely within the feature (other than any incidental part at the endpoints), and the points **407 and 409** maximum the component corresponding to the width. In aspects, the width **309** of a feature **214e** can be about 500 nanometers (nm) or more, about 1 μm or more, about 2 μm or more, about 5 μm or more, about 10 μm or more, about 20 μm or more, about 30 μm or more, about 50 μm or more, about 80 μm or more, about 100 μm or more, about 200 μm or less, about 150 μm or less, about 120 μm or less, about 100 μm or less, about 80 μm or less, about 50 μm or less, about 30 μm or less, about 20 μm or less, about 10 μm or less, or about 5 μm or less. In aspects, the width **309** of a feature **214e** can be in a range from about 500 nm to about 200 μm , from about 1 μm to about 150 μm , from about 2 μm to about 120 μm , from about 5 μm to about 100 μm , from about 10 μm to about 80 μm , from about 20 μm to about 50 μm , from about 30 μm to about 50 μm , or any range or subrange therebetween. In aspects, the width **309** of a feature **214e** can be about 50 μm or less, for example in a range from about 500 nm to about 50 μm , from about 5 μm to about 50 μm , from about 10 μm to about 50 μm , from about 20 μm to about 30 μm , or any range or subrange therebetween. In aspects, as shown in **FIGS. 1-2**, a set of features and/or all of the features of the plurality of features can have substantially the same and/or the same width. Alternatively, in aspects, although not shown, a width of one or more features of the plurality of features can be different than a width of another feature of the plurality of features.

[0086] Throughout the disclosure, a depth of the feature is the dimension perpendicular to the width in the plane perpendicular to the feature axis. For example, with reference to **FIG. 4**, the depth **411** of the feature **214e** is the maximum component of a distance between two points **403 and 405** on the periphery of the feature **214e** that is in the plane perpendicular to the axis **316d**, the component is perpendicular to a direction (e.g., direction **104**) of the width **309**, a path between the points **403 and 405** is entirely within the feature **214e** (other than any incidental part at the endpoints), and the points **403 and 405** maximize the component. In aspects, although not shown, the depth can be substantially equal to the width. Alternatively, as shown, the depth **411** can be less than the

width **309**. In aspects, the depth **411** can be within one or more of the ranges discussed above for the width **309**.

[0087] Throughout the disclosure, a “lateral spacing” refers to a minimum distance between adjacent features (that are not aligned along a common axis) measured in a cross-section (e.g., plane) perpendicular to the thickness direction as a distance between points on the corresponding periphery of the features of the adjacent features. For example, with reference to **FIG. 3**, the lateral spacing **305** between adjacent features **214a** and **214d** (that are not aligned along a common axis, e.g., **301** or **303**, with one another) is measured in a cross-section perpendicular to the direction **102** of the article thickness **109** (e.g., plane extending along dashed line **215** and/or direction **104**) between point **311a** (on feature **214a**) and point **315d** (on feature **214d**) on the periphery of the corresponding (adjacent) features **214a** and **214d** that are as close together as possible in the cross-section, where lateral spacing is the smallest distance of all cross-sections (perpendicular to the thickness direction). Consequently, it is to be noted that the lateral spacing is less than a distance between axes that the adjacent features extend along (e.g., an on-center distance) since the lateral spacing is measured between points on the periphery of the adjacent features. In aspects, the lateral spacing **305** between an adjacent pair of features can be about 30 μm or more, about 50 μm or more, about 70 μm or more, about 100 μm or more, about 120 μm or more, about 150 μm or more, about 170 μm or more, about 200 μm or more, about 300 μm or less, about 270 μm or less, about 250 μm or less, about 220 μm or less, about 200 μm or less, about 170 μm or less, about 150 μm or less, about 120 μm or less, about 100 μm or less, or about 70 μm or less. In aspects, the lateral spacing **305** between an adjacent pair of features can be in a range from about 30 μm to about 300 μm , from about 30 μm to about 270 μm , from about 50 μm to about 250 μm , from about 50 μm to about 220 μm , from about 70 μm to about 200 μm , from about 70 μm to about 170 μm , from about 100 μm to about 150 μm , from about 120 μm to about 150 μm , or any range or subrange therebetween. In further aspects, the lateral spacing of substantially all or all adjacent pairs of features can be within one or more of the ranges discussed above in this paragraph. In further aspects, the lateral spacing of substantially all and/or all of the adjacent pairs of features can be substantially the same and/or the same.

[0088] Throughout the disclosure, an in-line spacing of an adjacent pair of features arranged in a common line and/or along a common axis is measured as a minimum distance in a direction of the substrate thickness between points on the corresponding periphery of the features of the adjacent features. For example, with reference to **FIG. 3**, the in-line spacing **307** between an adjacent pair of features **214** and **214b** that are in a common line between the first major surface and the second major surface and/or are aligned along a common axis **301** (i.e., colinear with axes **316a** and **316b**) is measured as a minimum distance in the direction **102** of the article thickness **109** (see **FIGS. 1-2**) between point **313a** or **317a** on the periphery of feature **214a** and point **311b** or **315b** of feature **214b**. In aspects, the in-line spacing **307** between an adjacent pair of features **214a** and **214b** can be about 5 μm or more, about 10 μm or more, about 20 μm or more, about 50 μm or more, about 70 μm or more, about 100 μm or more, about 120 μm or more, about 150 μm or more, about 300 μm or less, about 250 μm or less, about 200 μm or less, about 150 μm or less, about 100 μm or less, or about 70 μm or less. In aspects, the in-line spacing **307** between an adjacent pair of features **214a** and **214b** can be in a range from about 5 μm to about 300 μm , from about 10 μm to about 250 μm , from about 20 μm to about 200 μm , from about 50 μm to about 150 μm , from about 70 μm to about 100 μm , or any range or subrange therebetween.

[0089] As utilized herein, the fracture toughness K_{IC} is measured by the double cantilever beam (DCB) method schematically illustrated in **FIG. 7**. The K_{IC} values were measured on glass-ceramic substrates before any chemical strengthening treatment. The DCB specimen geometry **701** is shown in **FIG. 7** with important parameters being the crack length a , applied load P , cross-sectional dimensions w (not shown – corresponding width of the sample other than a location with the crack-guiding groove) and $2h$, and the thickness of the crack-guiding groove b (not shown). The samples were cut into rectangles of width $2h = 1.25$ cm and a thickness ranging from $w = 0.3$ mm to 1 mm with the overall length of the sample (which is not a critical dimension) varying from 5 cm to 10 cm. Holes **703a** and **703b** were drilled on both ends with a diamond drill to provide a means of attaching the sample to a sample holder and to the load (for applying applied load P). A crack “guiding groove” (crack-guiding groove) was cut down the length of the sample on both flat faces using a wafer dicing saw with a diamond blade, leaving a “web” of material,

approximately half the total plate thickness (dimension ***b*** perpendicular to the view shown in **FIG. 7** and corresponding to the thickness present between edges **705a** and **705b** of the crack-guiding groove), with a height of 180 μm corresponding to the blade thickness (corresponding to a distance between edges **705a** and **705b** of the crack-guiding groove). The high precision dimensional tolerances of the dicing saw allow for minimal sample-to-sample variation. The samples were mounted in a metal sample holder with a steel wire in the bottom hole of the sample. The samples were also supported on the opposite end to keep the samples level under low loading conditions. A spring in series with a load cell (FUTEK, LSB200) was hooked to the upper hole **703a** which was then extended, to gradually apply load ***p***, using rope and a high precision slide. The crack was monitored using a microscope having a 5 μm resolution attached to a digital camera and a computer. The applied stress intensity, K_P , was calculated using the following equation (III):

$$K_P = \left[\frac{P \cdot a}{(w \cdot b)^{0.5} h^{1.5}} \right] \left[3.47 + 2.32 \frac{h}{a} \right]$$

For each sample, a crack was first initiated at the tip of the web, and then the starter crack was carefully sub-critically grown until the ratio of dimensions ***a/h*** was greater than 1.5, which is required for the above equation to accurately calculate stress intensity. At this point the crack length ***a*** was measured and recorded using a traveling microscope with 5 μm resolution. A drop of toluene was then placed into the crack groove and wicked along the entire length of groove by capillary forces, pinning the crack from moving until the fracture toughness is reached. The load ***p*** was then increased until sample fracture occurred, and the critical stress intensity K_{IC} calculated from the failure load and sample dimensions, with K_P being equivalent to K_{IC} due to the measurement method. As shown in **FIG. 7**, samples of the glass-ceramic article comprise a plurality of features **711** extending through the crack-guiding groove (with only 4 feature lines and/or features shown in **FIG. 7**, although it is to be understood that more features can be present in other aspects, for example spanning an entire dimension of the sample).

[0090] In aspects, the fracture toughness K_{IC} of the glass-ceramic article can be about 1.9 $\text{MPa}\sqrt{\text{m}}$ or more (e.g., about 1.90 $\text{MPa}\sqrt{\text{m}}$ or more), about 1.93 $\text{MPa}\sqrt{\text{m}}$ or more, about 1.95 $\text{MPa}\sqrt{\text{m}}$ or more, about 1.97 $\text{MPa}\sqrt{\text{m}}$ or more, about 2.00 $\text{MPa}\sqrt{\text{m}}$ or more (e.g., about 2.0 $\text{MPa}\sqrt{\text{m}}$ or more), about 2.03 $\text{MPa}\sqrt{\text{m}}$ or more, about 2.05 $\text{MPa}\sqrt{\text{m}}$ or more, about

2.07 MPa√m or more, about 2.10 MPa√m or more (e.g., about 2.1 MPa√m or more), about 2.20 MPa√m or less (e.g., about 2.2 MPa√m or less), about 2.17 MPa√m or less, about 2.15 MPa√m or less, about 2.12 MPa√m or less, about 2.10 MPa√m or less (e.g., about 2.1 MPa√m or less), about 2.07 MPa√m or less, about 2.05 MPa√m or less, about 2.03 MPa√m or less, or about 2.00 MPa√m or less (e.g., about 2.0 MPa√m or less). In aspects, the fracture toughness K_{IC} of the glass-ceramic article can be in a range from about 1.9 MPa√m to about 2.2 MPa√m (e.g., from about 1.90 MPa√m to about 2.20 MPa√m), from about 1.93 MPa√m to about 2.17 MPa√m, from about 1.95 MPa√m to about 2.15 MPa√m, from about 1.97 MPa√m to about 2.12 MPa√m, from about 2.00 MPa√m to about 2.10 MPa√m (e.g., from about 2.0 MPa√m to about 2.1 MPa√m), from about 2.03 MPa√m to about 2.07 MPa√m, from about 2.05 MPa√m to about 2.07 MPa√m, or any range or subrange therebetween. In exemplary aspects, the fracture toughness K_{IC} of the glass-ceramic article can be about 1.9 MPa√m or more, from about 1.95 MPa√m to about 2.15 MPa√m, or from about 2.00 MPa√m to about 2.1 MPa√m. As discussed herein, the plurality of features interior to the glass-ceramic article increase a fracture toughness K_{IC} of the glass-ceramic article by deflecting cracks and/or interrupting crack propagation within the glass-ceramic article.

[0091] In aspects, a fracture toughness K_{IC} of the glass-ceramic article (in accordance with aspects of the present disclosure) can be greater than a corresponding fracture toughness K_{IC} of another glass-ceramic article identical to the glass-ceramic article but without the plurality of features. In further aspects, the fracture toughness K_{IC} of the glass-ceramic article (in accordance with aspects of the present disclosure) can be greater than a corresponding fracture toughness K_{IC} of another glass-ceramic article identical to the glass-ceramic article but without the plurality of features (as a percentage of the fracture toughness K_{IC} of the another glass-ceramic article) can be about 5% or more, about 7% or more, about 10% or more, about 12% or more, about 15% or more, about 17% or more, about 25% or less, about 22% or less, about 20% or less, about 17% or less, about 15% or less, or about 12% or less. In further aspects, the fracture toughness K_{IC} of the glass-ceramic article (in accordance with aspects of the present disclosure) can be greater than a corresponding fracture toughness K_{IC} of another glass-ceramic article identical to the glass-ceramic article but without the plurality of features (as a percentage of the fracture

toughness K_{IC} of the another glass-ceramic article) can be in a range from about 5% to about 25%, from about 7% to about 22%, from about 10% to about 20%, from about 12% to about 20%, from about 15% to about 17%, or any range or subrange therebetween. In exemplary aspects, the increase in fracture toughness K_{IC} can be about 5% or more, from about 10% to about 20%, or from about 12% to about 17%.

[0092] Methods of making a glass-ceramic article comprising a plurality of features will now be discussed with reference to the optical apparatus shown in **FIGS. 5-6**. In aspects, methods can use an optical apparatus **501** in a method of making a glass-ceramic article comprising a plurality of features. Referring now to **FIG. 5**, an optical apparatus **501** for producing the laser beam **509** that is phase modified such that it forms a line focus **601** (see **FIG. 6**) within the substrate (e.g., glass-ceramic) **a** and has a quasi-non-diffracting character in the substrate using the phase-altering optical element **511** is schematically depicted. The optical apparatus **501** can include the laser **507** that outputs the laser beam **509**, the phase-altering optical element **511**, and, in some aspects, a lens assembly **515**. The laser **507** may be configured to output laser beams **509**, for example, pulsed laser beams or continuous wave laser beams. In aspects, the laser **507** may output a laser beam **509** comprising an optical wavelength of about 200 nm or more, about 300 nm or more, about 500 nm or more, about 700 nm or more, about 900 nm or more, about 1100 nm or more, about 1500 nm or less, about 1300 nm or less, about 1200 nm or less, about 1100 nm or less, about 1000 nm or less, about 900 nm or less, about 800 nm or less, about 700 nm or less, 500 nm or less, or about 400 nm or less. In aspects, the laser **507** may output a laser beam **509** comprising an optical wavelength in a range from about 200 nm to about 1500 nm, from about 300 nm to about 1500 nm, from about 500 nm to about 1300 nm, from about 500 nm to about 1200 nm, from about 700 nm to about 1100 nm, from about 700 nm to about 1000 nm, from about 700 nm to about 900 nm, or any range or subrange therebetween. For example, optical wavelengths of a laser beam emitted by the laser can be 1064 nanometers (nm), 1030 nm, 532 nm, 530 nm, 355 nm, 343 nm, or 266 nm, or 215 nm. In aspects, the laser **507** may output a laser beam **509** comprising an optical wavelength of about 700 nm or more, for example, in a range from about 700 nm to about 1500 nm, from about 700 nm to about 1300 nm, from about 700 nm to about 1200 nm, from about 900 nm to about 1100 nm, from about 900 nm to about 1000 nm, or any range or subrange

therebetween. In exemplary aspects, the laser 507 may output a laser beam 509 comprising an optical wavelength in a range from about 300 nm to about 1500 nm or from about 700 nm to about 1200 nm.

[0093] The laser beam 509 used to form features in the substrate may be well suited for materials that are transparent to the selected laser wavelength and the substrate may be positioned such that the laser beam 509 output by the laser 507 irradiates the substrate, for example, after impinging on the phase-altering optical element 511 and thereafter, the lens assembly 515. Further, the beam path 513 may extend from the laser 507 to the substrate such that when the laser 507 outputs the laser beam 509, laser beam 509 traverses (or propagates along) the beam path 513. In further aspects, the laser 507 can comprise a gas laser, an excimer laser, a dye laser, or a solid-state laser. Example aspects of gas lasers include helium, neon, argon, krypton, xenon, helium-neon (HeNe), xenon-neon (XeNe), carbon dioxide (CO₂), carbon monoxide (CO), copper (Cu) vapor, gold (Au) vapor, cadmium (Cd) vapor, ammonia, hydrogen fluoride (HF), and deuterium fluoride (DF). Example aspects of excimer lasers include chlorine, fluorine, iodine, or dinitrogen oxide (N₂O) in an inert environment comprising argon (Ar), krypton (Kr), xenon (Xe), or a combination thereof. Example aspects of dye lasers include those using organic dyes, for example, rhodamine, fluorescein, coumarin, stilbene, umbelliferone, tetracene, or malachite green dissolved in a liquid solvent. Example aspects of solid-state lasers include crystal lasers, fiber lasers, and laser diodes. Crystal-based lasers comprise a host crystal doped with a lanthanide, or a transition metal. Example aspects of host crystals include yttrium aluminum garnet (YAG), yttrium lithium fluoride (YLF), yttrium orthoaluminate (YAL), yttrium scandium gallium garnet (YSSG), lithium aluminum hexafluoride (LiSAF), lithium calcium aluminum hexafluoride (LiCAF), zinc selenium (ZnSe), zinc sulfide (ZnS), ruby, forsterite, and sapphire. Example aspects of dopants include neodymium (Nd), titanium (Ti), chromium (Cr), cobalt (Co), iron (Fe), erbium (Er), holmium (Ho), thulium (Tm), ytterbium (Yb), dysprosium (Dy), cerium (Ce), gadolinium (Gd), samarium (Sm), and terbium (Tb). Example aspects of solid crystals include ruby, alexandrite, chromium fluoride, forsterite, lithium fluoride (LiF), sodium chloride (NaCl), potassium chloride (KCl), and rubidium chloride (RbCl). Laser diodes can comprise heterojunction or PIN diodes with three or more materials for the respective p-type,

intrinsic, and n-type semiconductor layers. Example aspects of laser diodes include AlGaInP, AlGaAs, InGaIn, InGaAs, InGaAsP, InGaAsN, InGaAsNSb, GaInP, GaAlAs, GaInAsSb, and lead (Pb) salts. Some laser diodes represent exemplary aspects because of their size, tunable output power, and ability to operate at room temperature (i.e., about 20°C to about 25°C).

[0094] In aspects, as depicted in **FIG. 5**, the lens assembly **515** can comprise two sets of lenses, each set comprising the first lens **519** positioned upstream of the second lens **521**. The first lens **519** may collimate the laser beam **509** within a collimation space **517** between the first lens **519** and the second lens **521** and the second lens **521** may focus the laser beam **509**. Further, the most downstream positioned second lens **521** of the lens assembly **515** may focus the laser beam **509** into the substrate, which may be positioned at an imaging plane of this second lens **521**. In aspects, the first lens **519** and the second lens **521** may each comprise plano-convex lenses. When the first lens **519** and the second lens **521** each comprise plano-convex lenses, the curvature of the first lens **519** and the second lens **521** may each be oriented toward the collimation space **517**. In other aspects, the first lens **519** may comprise other collimating lenses and the second lens **521** may comprise a meniscus lens, an aspherical lens, or another higher-order corrected focusing lens. In operation, the lens assembly **515** may control the position of the line focus **601** along the beam path **513**. Further, the lens assembly **515** may comprise an 8F lens assembly, as depicted in **FIG. 5**, a 4F lens assembly comprising a single set of first and second lenses **519**, **521**, or any other known or yet to be developed lens assembly **515** for focusing the laser beam **509** into the line focus **601** and/or along the beam path **513**. Moreover, it should be understood that some aspects may not include the lens assembly **515** and instead, the phase-altering optical element **511** may focus the laser beam **509** into the line focus **601**.

[0095] Referring still to **FIG. 5**, the phase-altering optical element **511** can be positioned within the beam path **513** between the laser **507** and the substrate **103**, in particular, between the laser **507** and the lens assembly **515** such that the laser beam **509** impinges on the phase-altering optical element **511** before the laser beam **509** is focused into the line focus **601** and directed into the substrate. In aspects, as shown in **FIG. 5**, the optical apparatus **501** can be configured such that the laser **507** is positioned such that the beam path **513** is redirected by the phase-altering optical element **511** and the laser beam

509 reflects off the phase-altering optical element **511** when the laser beam **509** impinges on the phase-altering optical element **511**. In further aspects, the phase-altering optical element **511** may comprise an adaptive phase-altering optical element **527**, for example, a spatial light modulator (SLM), a deformable mirror, an adaptive phase plate (ADP), or any other optical element configured to be actively altered to control a change in phase applied by the optical element to the laser beam **509**. In even further aspects, the SLM can be optically controlled and/or digitally controlled. For example, although not shown, the laser can be positioned such that the beam path extends through the phase-altering optical element (e.g., an aspheric optical element, a static phase plate, and/or an axicon – elliptical axicon or oblong axicon) and the laser beam traverses the phase-altering optical element when the laser beam impinges on the phase-altering optical element. An exemplary aspect of a static phase plate is a beam block, which can comprise portions that block (e.g., reflect) a portion of the laser beam **509** while comprising portions that focus and/or alter the phase of the laser beam **509**. Thus, in aspects, the phase-altering optical element **511** can be a refractive optical element and in other aspects, the phase-altering optical element **511** can be a reflective optical element. In operation, impinging on the laser beam **509** on the phase-altering optical element **511** alters the phase of the laser beam **509** and when directed into the substrate, a portion of the laser beam **509** comprising the line focus **601** within the substrate can comprise a different angle within the substrate **103** than the angle of the beam path **513** through the lens assembly due to differences in the index of refraction between the material of the substrate and the medium that the beam path **513** travels through. For simplicity, the angle of the line focus **601** and the beam path **513** are shown as the same with the understanding that the angles may be different in practice.

[0096] Without wishing to be bound by theory, after the laser beam **509** has been phase modified by the phase-altering optical element **511**, the laser beam **509** can be aberrated when the laser beam is upstream from the substrate, for example, when the laser beam **509** is in free space, and the laser beam **509** is aberrated when the laser beam **509** is incident on the first major surface of the substrate. Once refracted at the first major surface of the substrate, the laser beam **509** can exhibit a quasi-non-diffracting character and thus has minimal to no aberrations within the substrate. Without wishing to be bound by theory, the conversion from an aberrated beam to a non-aberrated beam at the first major surface

of the substrate can be accompanied by an increase in Rayleigh range, which may increase with increasing deviation of the angle of incidence. Without wishing to be bound by theory, the laser beam **509** may comprise a higher Rayleigh range within the substrate than in free space or in positions upstream or incident to the first major surface. For example, the Rayleigh range of the laser beam **509** within the substrate may be 10 to 1000 times greater than the Rayleigh range outside (e.g. upstream) the substrate. For example, after phase modification, the laser beam **509** outside (e.g. upstream) the substrate may comprise a Rayleigh range of 30 μm and the Rayleigh range of the laser beam **509** within the substrate may be 1 mm. Indeed, in aspects, the laser beam **509** can be refracted at the first major surface of the substrate. The refracting can increase the dimensionless divergence factor F_D of a Rayleigh range Z_R of the laser beam **509** by a factor of at least 10, for example, from 10 to 1000, from 10 to 500 from 10 to 100, or the like.

[0097] Referring again to FIG. 5, in aspects, the phase-altering optical element **511** may comprise an adaptive phase-altering optical element **527**, which can apply a phase alteration to the laser beam **509** using a phase mask. The adaptive phase-altering optical element **527** may be communicatively coupled to a controller **503**, for example, using one or more communications pathways **505**, which may comprise any pathway for providing power signals, control signals, or the like, for example, optical fiber, electrical wire, wireless protocols, or the like. In operation, the controller **503** may provide control signals to the adaptive phase-altering optical element **527** to control the specific phase alteration (e.g., modulation, phase mask, or the like) applied by the adaptive phase-altering optical element **527** such that the adaptive phase-altering optical element **527** applies a specific phase alteration to the laser beam **509**, for example, based on a phase function. In aspects, the adaptive phase-altering optical element **527** can comprise a spatial light modulator (SLM), which is a transmissive or reflective device that may spatially modulate the amplitude and/or the phase of a laser beam **509** in at least one dimension. In operation, the spatial light modulator (SLM) may apply a selective, configurable phase alteration to the laser beam **509** based on control signals from the controller **503**. In aspects, the adaptive phase-altering optical element **527** can comprise a deformable mirror, which is a mirror whose surface can be deformed in response to control signals, for example, control signals from the controller **503**, to alter the wavefront of the laser beam **509**, which may alter the

phase of the laser beam **509**. For example, a deformable mirror may be configured to apply a phase mask. Further, in aspects, the adaptive phase-altering optical element **527** can comprise an adaptive phase plate, which is a phase plate (or phase plate assembly) that can apply selective and controllable phase alteration to the laser beam **509** in response to control signals, for example, control signals from the controller **503**. For example, the adaptive phase plate may be two or more phase plates moveable relative to one another (e.g., based on control signals from the controller **503**) to alter the phase change they apply to the laser beam **509** based on their relative positioning.

[0098] In aspects, methods of forming the plurality of features in a glass-ceramic article comprise providing a glass-ceramic article. Glass-ceramic articles can be provided by purchase or formed by ceramming (e.g., heating to crystallize and/or grow crystals in) a glass-based substrate formed from a variety of ribbon forming techniques, for example, slot draw, down-draw, fusion down-draw, up-draw, press roll, redraw, or float. In aspects, methods can comprise adjusting a lens (e.g., a lens of the lens assembly **515**, first lens **519**, second lens **521**, and/or adaptive phase-altering optical element **527**) to create a line focus (e.g., line focus **601**) within the glass-ceramic article (e.g., substrate **103**) as shown in **FIGS. 5-6**. In aspects, the glass-ceramic article (e.g., substrate **103**) can be positioned on a contact surface **525** of a stage **523** (e.g., with the second major surface **107** contacting the contact surface **525**). The stage **523** can be positioned (e.g., rotated) to achieve a predetermined angle for the features (e.g., with the beam path **513** within the substrate **103** corresponding to the resulting axis **301** of one or more features of the plurality of features), for example, the stage can be positioned and/or adjusted by a signal sent from the controller **503** along communication pathway **529**.

[0099] In aspects, methods can comprise emitting a burst of pulses from the laser **507**, for example, traveling along the beam bath **513**. In further aspects, an optical wavelength that the laser **507** is configured to emit and/or an optical wavelength of the burst of pulses can be within one or more of the corresponding ranges discussed above (e.g., from about 300 nm to about 1500 nm or from about 700 nm to about 1200 nm). In further aspects, a pulse width of one or more pulses (e.g., in the burst of pulses) can be about 500 femtoseconds (fs) or more, about 1 picosecond or more (ps), about 5 ps or more, about 50 ps or more, about 500 ps or more, about 1 nanosecond (ns) or more, about 2 ns or

more, about 5 ns or more, about 10 ns or less, about 50 ns or less, about 20 ns or less, about 5 ns or less, about 2 ns or less, about 1 ns or less, about 500 ps or less, about 200 ps or less, about 100 ps or less, about 50 ps or less, about 20 ps or less, about 10 ps or less, or about 5 ps or less. In further aspects, a pulse width of one or more pulses (e.g., in the burst of pulses) can be in a range from about 500 fs to about 50 ns, from about 1 ps to about 20 ns, from about 5 ps to about 5 ns, from about 50 ps to about 2 ns or less, from about 500 ps to about 1 ns, or any range or subrange therebetween. In further aspects, a pulse length of a pulse of the burst of pulses can be in the picosecond range, for example, from about 1 ps to about 500 ps, from about 1 ps to about 100 ps, from about 1 ps to about 50 ps, from about 1 ps to about 20 ps, from about 1 ps to about 10 ps, from about 5 ps to about 10 ps, or any range or subrange therebetween. In further aspects, an energy of a pulse of the burst of pulses can be about 1 microJoule (μJ) or more, about 5 μJ or more, about 10 μJ or more, about 20 μJ or more, about 50 μJ or less, about 40 μJ or less, about 30 μJ or less, about 20 μJ or less, or about 10 μJ or less. In further aspects, an energy of a pulse of the burst of pulses can be in a range from about 1 μJ to about 50 μJ , from about 5 μJ to about 40 μJ , from about 10 μJ to about 30 μJ , from about 10 μJ to about 20 μJ , or any range or subrange therebetween. In further aspects, a shape of a pulse of the burst of pulses can be Gaussian, Bessel, or Airy. In further aspects, pulses of the burst of pulse can be generated at a repetition rate of about 50 kiloHertz (kHz) or more, about 100 kHz or more, about 200 kHz or more, about 500 kHz or more, about 1 MegaHertz (MHz) or less, about 500 kHz or less, about 300 kHz or less, or about 100 kHz or less. In further aspects, pulses of the burst of pulse can be generated at a repetition rate in a range from about 50 kHz to about 1 MHz, from about 100 kHz to about 500 kHz, from about 200 kHz to about 300 kHz, or any range or subrange therebetween. In further aspects, number pulses in the burst of pulses can be in a range from about 100 to about 1,500, from about 100 to about 1,000, from about 100 to about 800, from about 300 to about 1,500, from about 300 to about 1,000, from about 300 to about 800, from about 600 to about 1,500, from about 600 to about 1,000, from about 600 to about 800, or any range or subrange therebetween.

[00100] In further aspects, as shown in **FIG. 5**, a burst of pulses travelling along the beam bath **513** can be transmitted through the lens (e.g., a lens of the lens assembly **515**, first lens **519**, second lens **521**, and/or adaptive phase-altering optical element **527**).

In even further aspects, the burst of pulses can impinge a spatial light modulator (SLM) to form a plurality of spatially distinct beam spots for each pulse of the burst of pulses that can form a set of features that are spatially distinct, although a SLM may not be present in other aspects. In further aspects, as shown in **FIGS. 5-6**, the burst of pulses can travel along the beam path **513** in a direction **502** towards the substrate **103** and impinge the glass-ceramic article (e.g., substrate **103**) to form the plurality of features (e.g., see plurality of features **111** and/or **211** in **FIGS. 1-2**). As discussed above, the pulse(s) of the burst of pulses can form the feature of the plurality of features by locally melting a portion of the primary ceramic phase to form an amorphous glass region associated with the feature. In further aspects, each pulse of the burst of pulses can form a feature of the plurality of features, although multiple pulses can impinge substantially the same location to collectively form a feature of the plurality of features in further aspects. In further aspects, as shown in **FIG. 6**, a pulse of the burst of pulses travelling along the beam path **513** can form a line focus **601** within the glass-ceramic article (e.g., substrate **103**). In even further aspects, a length of the line focus **601** in the substrate **103** can be about 10 μm or more, about 20 μm or more, about 50 μm or more, about 100 μm or more, about 200 μm or more, about 500 μm or more, about 1 mm or less, about 800 μm or less, about 400 μm or less, about 200 μm or less, about 100 μm or less, about 80 μm or less, or about 40 μm or less. In even further aspects, a length of the line focus **601** in the substrate **103** can be in a range from about 10 μm to about 1 mm, from about 20 μm to about 800 μm , from about 50 μm to about 400 μm , from about 100 μm to about 200 μm , or any range or subrange therebetween. Additionally or alternatively, a length of the line focus **601** can be within one or more of the ranges discussed above for the length of a feature of the plurality of features. In further aspects,

EXAMPLES

[00101] Examples 1-4 relate to methods of creating a plurality of features within a glass-ceramic article using a pulsed laser, as described above. The pulsed laser was a Pharos ultrafast laser system (available from Light Conversion) that was operated with the solid-state laser configured to produce pulse with an optical wavelength centered at 1030 nm, a 1 ps pulse width, and a 200 kHz repetition rate, corresponding to an energy of about 5 μJ per pulse. The laser beam was focused using an 40X objective lens with a numerical

aperture of 0.65 (available from Olympus) to be focused within the glass-ceramic substrate. Unless otherwise indicated, the features were formed with an on-center distance of 50 μm between adjacent features (not in a line – which corresponds to a smaller lateral spacing 305 shown in **FIG. 3**).

[00102] For Examples 1-2, the beam shape was a Bessel beam configured to form 6 features in a line (internal to the substrate and extending between the first major surface and the second major surface). For Examples 3-44, the beam shape was a Gaussian beam configured to form one long feature (internal to the substrate and extending between the first major surface and the second major surface). For Examples 1-3, the tilt angle (see tilt angle 321 in **FIG. 3**) was 0°, 30°, and 45°, respectively. For Examples 4 -5, the title angle was 60° and 75°, respectively.

[00103] For Examples 1-4, the substrate comprised a substrate comprising Composition 1 (61.2 mol% SiO₂, 1.5 mol% Al₂O₃, 24.5 mol% Li₂O, 2 mol% Na₂O, 6.5 mol% CaO, 1.7 mol% P₂O₅, and 1.6 mol% F⁻) that was cerammed at 750°C for 5 minutes to produce a glass-ceramic with lithium disilicate and apatite crystal phases (i.e., primary ceramic phase).

[00104] As discussed above, **FIG. 8** (Example 3) shows the plurality of features (e.g., features 805a, 805b, 805c, and/or 805d – corresponding to a second set of features 913 in **FIG. 9**) comprise an amorphous glass phase surrounded by a primary ceramic phase 801 of the substrate (e.g., glass-ceramic article).

[00105] Also, **FIG. 9** (Example 3) shows a top view of the substrate 103 (looking down the first major surface 105 of the substrate 103 that is perpendicular to the view shown in **FIG. 7**). Originally, the outline of where the laser impinged the surface was visible (although the laser did not form features extending to the surface), which is made clearer using the boxes in **FIG. 9**. As shown in **FIG. 9**, a first set of features 911 was formed as two rows of features 903a and 903b that are staggered relative to one another. Also, a second set of features 913 was formed as four rows of features 905a, 905b, 905c and 905d in a staggered (or checkboard) pattern. Portions 915a and 915b are seen in **FIG. 9** that correspond to regions cut by the dicing saw in preparing the sample for the double-cantilever beam method.

[00106] **FIG. 10** (Example 3) shows a side view of the substrate (corresponding to the view shown in **FIG. 7**) in the configuration for the double cantilever beam configuration used to determine fracture toughness (discussed above) but the method is stopped before fracture for this view. Consequently, edges **1005a** and **1005b** (in **FIGS. 10-13**) correspond to edges **705a** and **705b** demarcating the edges of the crack-guiding groove. As shown in **FIG. 10**, a plurality of features **1011** corresponding to three sets of features are shown as straight lines (black) for clarity. As indicated, going from left to right, the first set of features corresponds to two lines of features (see first set of features **911** in **FIG. 9**), the second set of features corresponds to four lines of features (see second set of features **913** in **FIG. 9**), and the third set of features corresponds to eight lines of features.

[00107] **FIG. 11** (Example 3) shows a side view of the substrate (corresponding to the view shown in **FIG. 7**) with crack deflection from the double-cantilever beam configuration (stopped before fracture but the same configuration that was used to determine fracture toughness). **FIG. 11** shows crack **1101** that was deflected (upwards) by the plurality features **1111** (corresponding to the second set of features **913** in **FIGS. 9-10**).

[00108] **FIG. 12** (Example 2) and **FIG. 13** (Example 1) also show side views of the substrate (corresponding to the view shown in **FIG. 7**) with crack deflection in the double-cantilever beam configuration (stopped before fracture but the same configuration that was used to determine fracture toughness). As shown in **FIG. 12**, the plurality of features **1211** with a tilt angle of 30° deflects the crack **1201** (upwards). As shown in **FIG. 13**, the plurality of features **1311** with a tilt angle of 0° also deflects the crack **1301** (downwards).

[00109] Table 1 presents the fracture toughness measured for Examples 1-4 and Comparative Example AA. Comparative Example AA is the same substrate (i.e., glass-ceramic article) that was used for Examples 1-4, but Comparative Example AA does not have any features. As shown in Table 1, Comparative Example had a fracture toughness K_{IC} of $1.76 \text{ MPa}\sqrt{\text{m}}$ while Examples 1-4 had fracture toughness K_{IC} values of $1.95 \text{ MPa}\sqrt{\text{m}}$ or more (from $1.95 \text{ MPa}\sqrt{\text{m}}$ to about $2.35 \text{ MPa}\sqrt{\text{m}}$). Also, as shown, Examples 1-5 increase the fracture toughness K_{IC} relative to Comparative Example AA by 10% or more (e.g., from 11% to about 35%).

Table 1: Fracture Toughness for Examples 1-4 and Comparative Example AA

Example	Tilt Angle	Fracture Toughness (K_{IC}) (MPa $\sqrt{m}$)	Increase (% versus AA)
1	0°	2.32	32
2	30°	2.16	23
3	45°	1.95	11
4	60°	2.00	14
AA	n/a	1.76	n/a

[00110] **FIG. 14** illustrates a magnified top cross-sectional view (see **FIG. 9**) of Example 4 after the fracture toughness was determined in the double-cantilever beam configuration. In **FIG. 14**, the features (e.g., features **1401**, **1411**, **1421**, and **1431**) were visible by the solid-black lines (forming an L-shape) with the dashed lines completing the outline of the feature. The features (e.g., features **1401**, **1411**, **1421**, and **1431**) correspond to height variation of the surface, where the crack propagation has left discernable deformations (also outlined in black) on the surface from crack deflection through the sample during testing to fracture. For example, the height associated with triangles **1403** and **1433** appear to concentrate at the corners of the features, which promotes crack deflection. Also, there are lines **1405** and additional shapes **1413** and **1423** that appear to correspond to be channeled to an adjacent set of rows (offset), which can deflect a propagating crack. Without wishing to be bound by theory, it is believed that the crack deflection seen in **FIG. 14** may be the result of one or more of (1) a lower strain energy in the features, (2) a weak interface between the features and the primary ceramic phase, and/or (3) a mismatch in the coefficient of thermal expansion (CTE) between the features and the primary ceramic phase.

[00111] **FIG. 15** illustrates a cross-section of Example 4 (similar to **FIG. 8**) but for different features and after the fracture toughness was determined in the double-cantilever beam configuration. In **FIG. 15**, features **1503** and **1505** are shown with the amorphous glass phase outlined in a roughly oval shape. Additionally, swooping shapes **1507** and **1509** are seen intersecting the bottom of the features **1503** and **1505** and

changing the bottom of the roughly oval shape, which indicates that the strain (and stress) associated with crack propagation was concentrated into the feature before and/or instead of continuing to propagate.

[00112] The embodiments of the disclosure can provide glass-ceramic articles including a plurality of features internal to the glass-ceramic article. As demonstrated by the Examples herein, the plurality of features interior to the glass-ceramic article increase a fracture toughness K_{IC} of the glass-ceramic article (e.g., relative to a glass-ceramic article without the plurality of features by 10% or more, from about 10% to about 35%, or from about 10% to about 20%). Without wishing to be bound by theory, it is believed that the plurality of features interior to the glass-ceramic article increases the fracture toughness K_{IC} by deflecting cracks and/or interrupting crack propagation within the glass-ceramic article. Also, a tilt angle of the features of the plurality of features can be controlled to further increase the fracture toughness.

[00113] Methods of the present disclosure can form the plurality of features interior to the glass-ceramic article by impinging a focused (e.g., line focus) laser beam (e.g., plurality of pulses) within the glass-ceramic article. The pulsed laser can quickly form the plurality of features. The shape and/or length of the features can be controlled by adjusting the beam shape, focusing optics, and other properties of an optical apparatus including the laser.

[00114] Directional terms as used herein—for example, up, down, right, left, front, back, top, bottom—are made only with reference to the figures as drawn and are not intended to imply absolute orientation.

[00115] It will be appreciated that the various disclosed aspects may involve features, elements, or steps that are described in connection with that aspect. It will also be appreciated that a feature, element, or step, although described in relation to one aspect, may be interchanged or combined with alternate aspects in various non-illustrated combinations or permutations.

[00116] It is also to be understood that, as used herein, the terms “the,” “a,” or “an,” mean “at least one,” and should not be limited to “only one” unless explicitly indicated to the contrary. For example, reference to “a component” comprises aspects

having two or more such components unless the context clearly indicates otherwise. Likewise, a “plurality” is intended to denote “more than one.”

[00117] As used herein, the term “about” means that amounts, sizes, formulations, parameters, and other quantities and characteristics are not and need not be exact, but may be approximate and/or larger or smaller, as desired, reflecting tolerances, conversion factors, rounding off, measurement error and the like, and other factors known to those of skill in the art. Ranges can be expressed herein as from “about” one particular value, and/or to “about” another particular value. When such a range is expressed, aspects include from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent “about,” it will be understood that the particular value forms another aspect. Whether or not a numerical value or endpoint of a range in the specification recites “about,” the numerical value or endpoint of a range is intended to include two aspects: one modified by “about,” and one not modified by “about.” It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint and independently of the other endpoint.

[00118] The terms “substantial,” “substantially,” and variations thereof, as used herein, are intended to note that a described feature is equal or approximately equal to a value or description. For example, a “substantially planar” surface is intended to denote a surface that is planar or approximately planar. Moreover, as defined above, “substantially similar” is intended to denote that two values are equal or approximately equal. In aspects, “substantially similar” may denote values within about 10% of each other, for example, within about 5% of each other, or within about 2% of each other.

[00119] Unless otherwise expressly stated, it is in no way intended that any method set forth herein be construed as requiring that its steps be performed in a specific order. Accordingly, where a method claim does not actually recite an order to be followed by its steps or it is not otherwise specifically stated in the claims or descriptions that the steps are to be limited to a specific order, it is in no way intended that any particular order be inferred.

[00120] While various features, elements, or steps of particular aspects may be disclosed using the transitional phrase “comprising,” it is to be understood that alternative aspects, including those that may be described using the transitional phrases “consisting

of” or “consisting essentially of,” are implied. Thus, for example, implied alternative aspects to an apparatus that comprises A+B+C include aspects where an apparatus consists of A+B+C and aspects where an apparatus consists essentially of A+B+C. As used herein, the terms “comprising” and “including”, and variations thereof shall be construed as synonymous and open-ended unless otherwise indicated.

[00121] The above aspects, and the features of those aspects, are exemplary and can be provided alone or in any combination with any one or more features of other aspects provided herein without departing from the scope of the disclosure.

[00122] It will be apparent to those skilled in the art that various modifications and variations can be made to the present disclosure without departing from the spirit and scope of the disclosure. Thus, it is intended that the present disclosure cover the modifications and variations of the aspects herein provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A glass-ceramic article comprising:
a first major surface, a second major surface opposite the first major surface, and an article thickness defined therebetween;
a primary ceramic phase; and
a plurality of features within an interior of the glass-ceramic article, the plurality of features comprising an amorphous glass phase, a height in a direction of the article thickness.
2. The glass-ceramic article of claim 1, wherein a minimum distance between a feature of the plurality of features and the first major surface is in a range from about 10 micrometers to about 100 micrometers.
3. The glass-ceramic article of any one of claims 1-2, wherein a tilt angle relative to the direction of the article thickness of a feature of the plurality of features is in a range from about 0° to about 60°.
4. The glass-ceramic article of any one of claims 1-3, wherein a first set of features of the plurality of features are arranged in a line between the first major surface and the second major surface.
5. The glass-ceramic article of claim 4, wherein the height of a first feature in the first set of features is in a range from about 5 micrometers to about 500 micrometers.
6. The glass-ceramic article of claim 4, wherein the height of a first feature in the first set of features as a percentage of the article thickness is in a range from about 5% to about 30%.
7. The glass-ceramic article of any one of claims 1-3, wherein the height of the feature of the plurality of features as a percentage of the article thickness is in a range from about 50% to about 95%.

8. The glass-ceramic article of any one of claims 1-7, wherein each feature of the plurality of features extends along a corresponding axis, and a distance between the axes of an adjacent pair of features of the plurality of features is in a range from about 30 micrometers to about 300 micrometers.

9. The glass-ceramic article of any one of claims 1-3, wherein each feature of the plurality of features extends along a corresponding axis, and a first axis of a first feature of the plurality of features is colinear with a second axis of a second feature of the plurality of features.

10. The glass-ceramic article of any one of claims 8-9, wherein a width of a feature of the plurality of features perpendicular to the axis of the feature is in a range from about 500 nanometers to about 200 micrometers.

11. The glass-ceramic article of any one of claims 1-10, wherein a fracture toughness K_{IC} of the glass-ceramic article is about $1.9 \text{ MPa}\sqrt{\text{m}}$ or more.

12. The glass-ceramic article of any one of claims 1-10, wherein a fracture toughness K_{IC} of the glass-ceramic article is greater than a fracture toughness K_{IC} of another glass-ceramic article identical to the glass-ceramic article but without the plurality of features by about 5% or more.

13. The glass-ceramic article of any one of claims 1-12, wherein the primary ceramic phase comprises β -spodumene, β -quartz, nepheline, cordierite, spinel, lithium disilicate, or a combination thereof.

14. The glass-ceramic article of any one of claims 1-13, wherein a feature of the plurality of features is surrounded by the primary ceramic phase.

15. A method of forming a plurality of features in a glass-ceramic article, the glass-ceramic article comprising a primary ceramic phase, a first major surface, a second major surface opposite the first major surface, and an article thickness defined between the first major surface and the second major surface, the method comprising:

- adjusting a lens to create a line focus within the glass-ceramic article;
- emitting a burst of pulses from a laser;
- transmitting the burst of pulses through the lens; and
- impinging the burst of pulses on the glass-ceramic article to form the plurality of features,

wherein the burst of pulses melts a portion of the primary ceramic phase to form a feature of the plurality of features comprising an amorphous glass phase, the plurality of features comprising a height in a direction of the article thickness, and the plurality of features are formed within an interior of the glass-ceramic article.

16. The method of claim 15, wherein a pulse of the burst of pulses comprising an energy in a range from about 1 microjoule to about 50 microjoules, and pulses of the burst of pulses are generated at a rate from about 50 kilohertz to about 1 megahertz.

17. The method of any one of claims 15-16, wherein an optical wavelength associated with the burst of pulses is in a range from about 300 nanometers to about 1500 nanometers, and a pulse width of a pulse of the burst of pulses is in a range from about 500 femtoseconds to about 50 nanoseconds.

18. The method of any one of claims 15-17, wherein a length of the line focus is in a range from about 10 micrometers to about 1 millimeter.

19. The method of any one of claims 15-18, further comprising impinging the burst of pulses on a spatial light modulator to generate a plurality of spatially distinct beam spots for each pulse of the burst of pulses, and impinging the plurality of spatially distinct beam spots on the generate a set of features of the plurality of features.

20. The method of any one of claims 15-19, wherein a minimum distance between a feature of the plurality of features and the first major surface is in a range from about 10 micrometers to about 100 micrometers.

21. The method of any one of claims 15-20, wherein a tilt angle relative to the direction of the height of a feature of the plurality of features is in a range from about 0° to about 60°.

22. The method of any one of claims 15-21, wherein a first set of features of the plurality of features are arranged in a line between the first major surface and a second major surface.

23. The method of any one of claims 15-21, wherein each feature of the plurality of features extends along a corresponding axis, and a first axis of a first feature of the plurality of features is colinear with a second axis of a second feature of the plurality of features.

24. The method of any one of claims 22-23, wherein the height of a first feature in the first set of features is in a range from about 5 micrometers to about 500 micrometers.

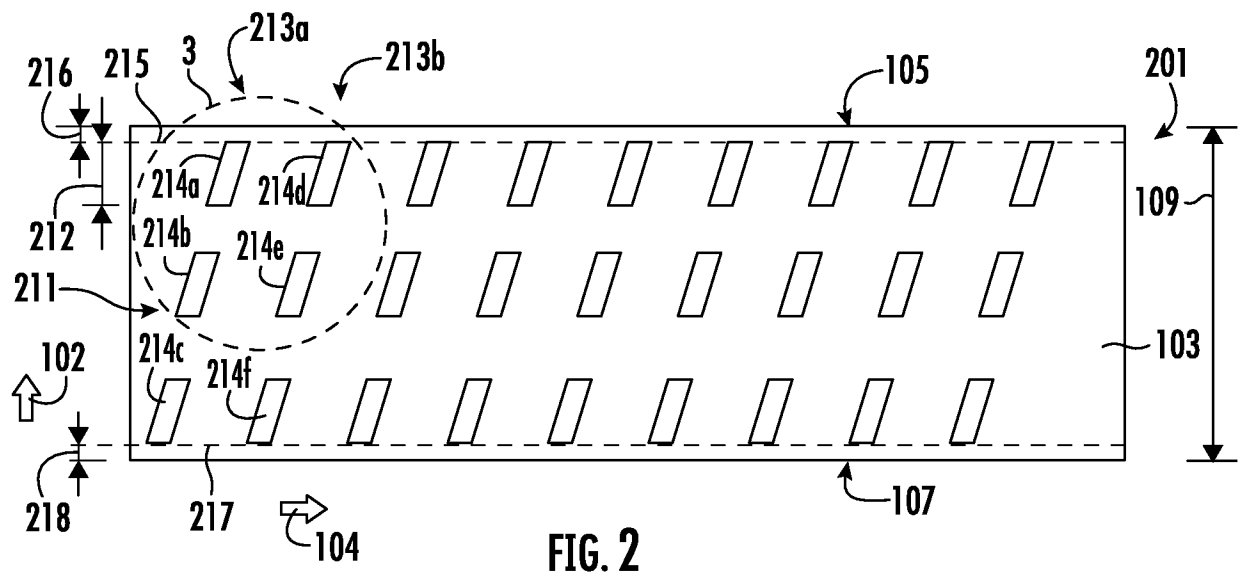
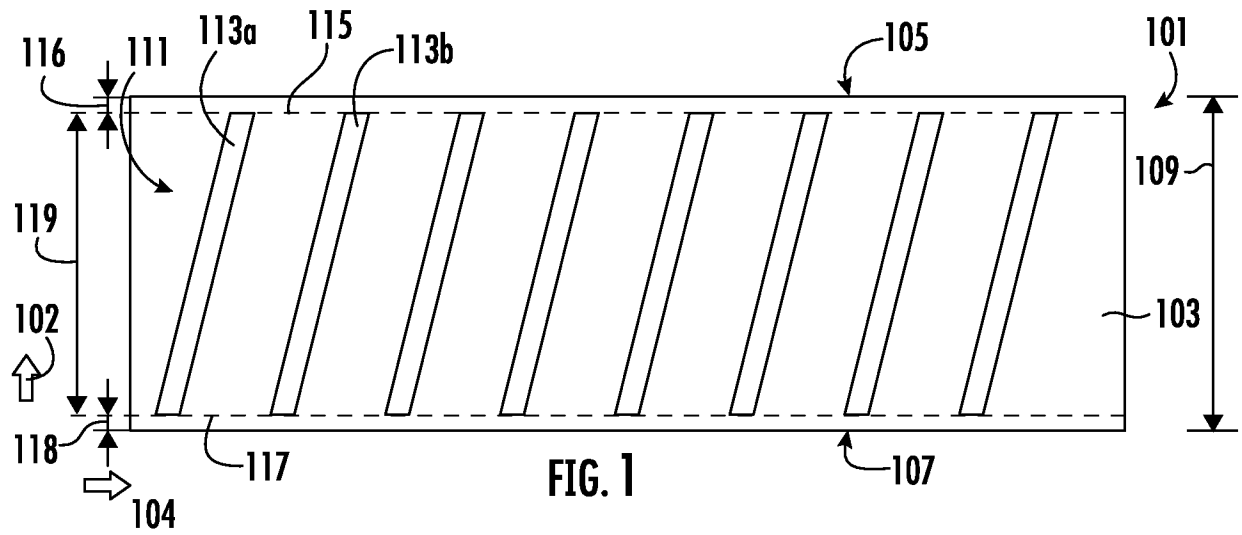
25. The method of any one of claims 15-21, wherein the height of the feature of the plurality of features as a percentage of the article thickness is in a range from about 50% to about 95%.

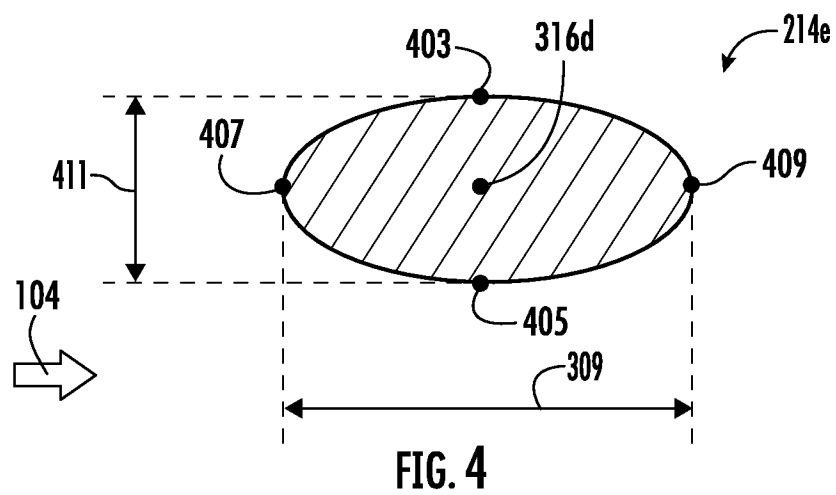
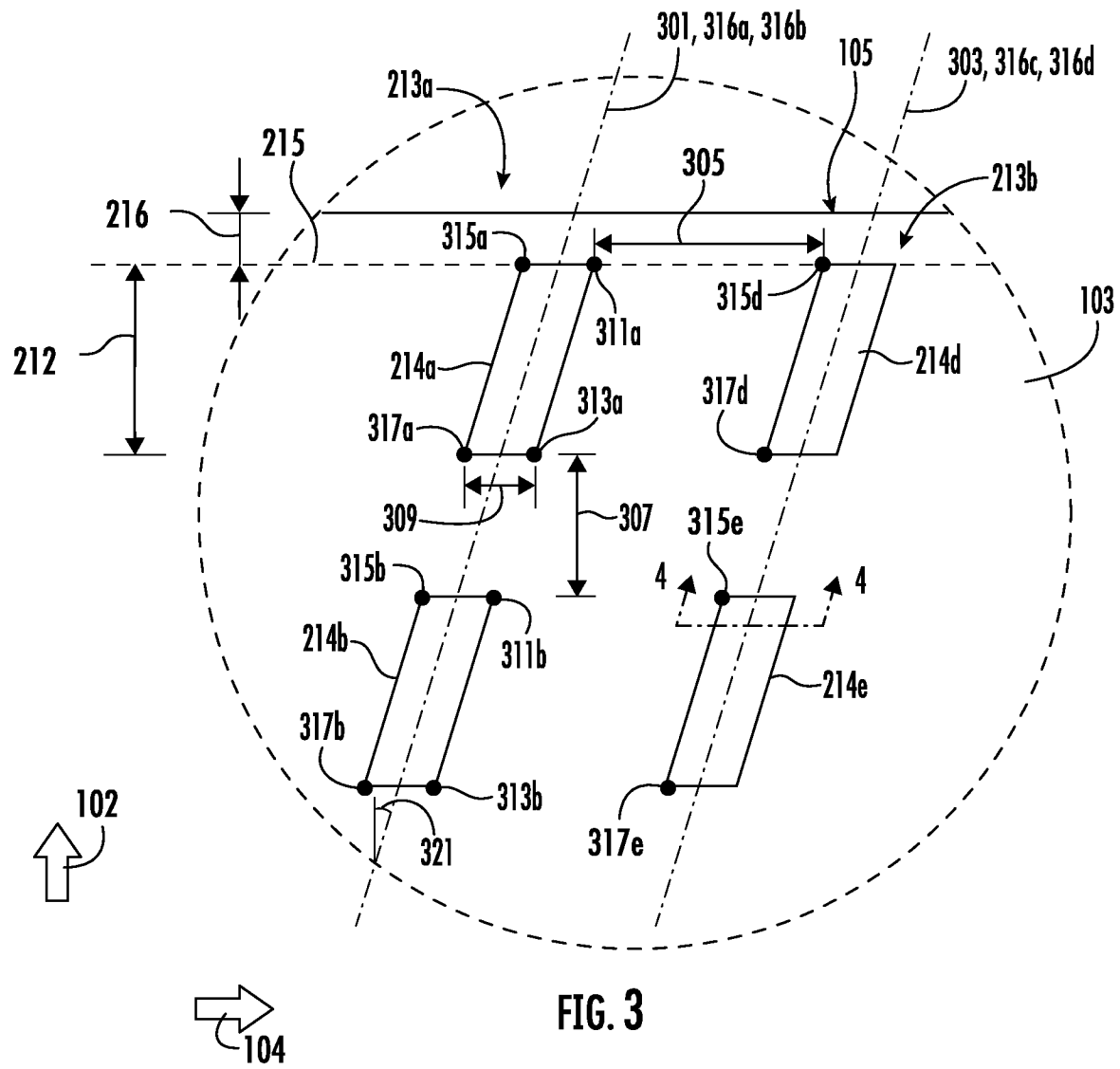
26. The method of any one of claims 22-24, wherein each feature of the plurality of features extends along a corresponding axis, and a distance between the axes of an adjacent pair of features of the plurality of features is in a range from about 30 micrometers to about 300 micrometers.

27. The method of any one of claims 15-26, wherein a fracture toughness K_{IC} of the glass-ceramic article is about $1.9 \text{ MPa}\sqrt{\text{m}}$ or more.

28. The method of any one of claims 15-26, wherein a fracture toughness K_{IC} of the glass-ceramic article is greater than a fracture toughness K_{IC} of another glass-ceramic article identical to the glass-ceramic article but without the plurality of features by about 5% or more.

29. The method of any one of claims 15-28, wherein a feature of the plurality of features is surrounded by the primary ceramic phase.





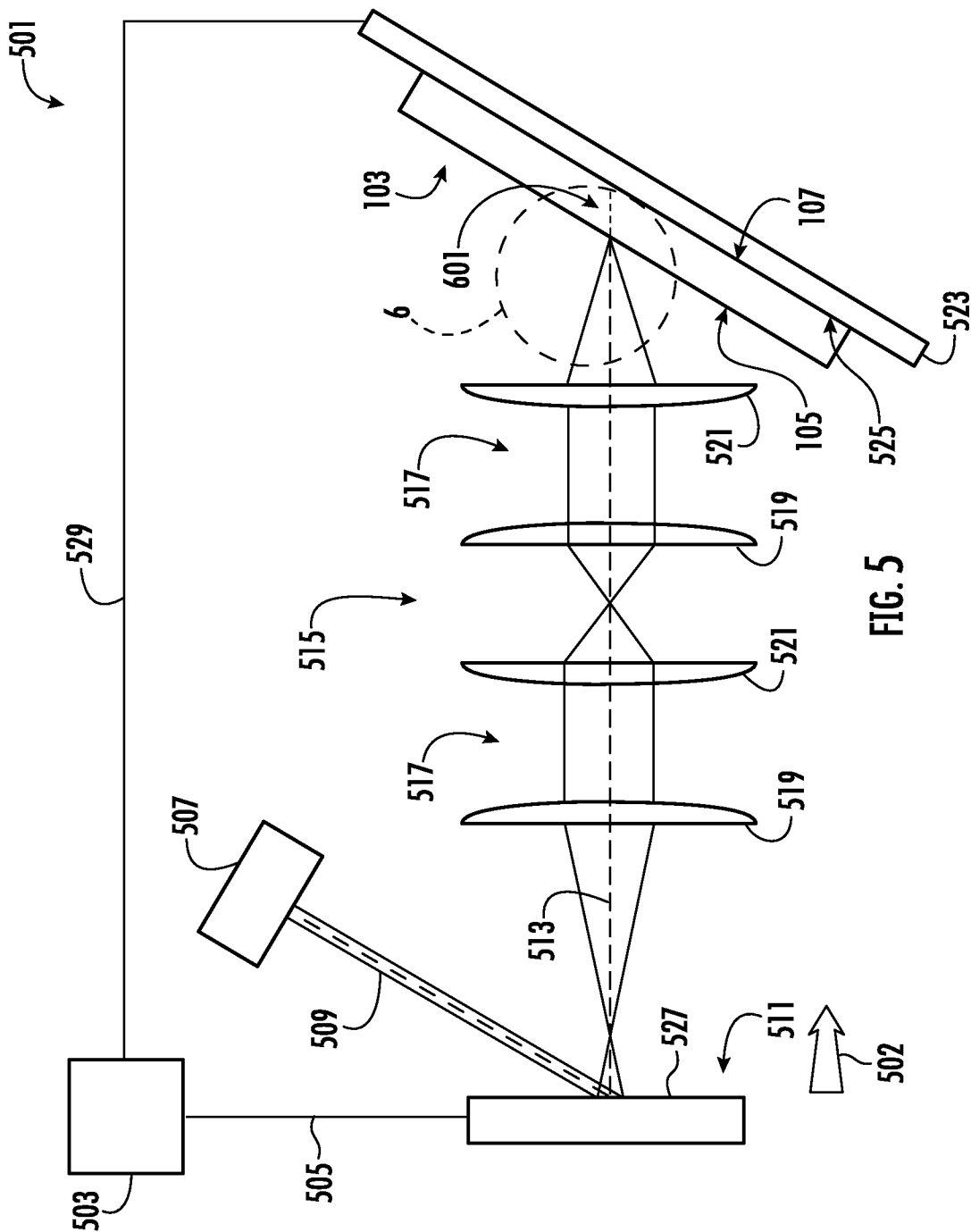


FIG. 5

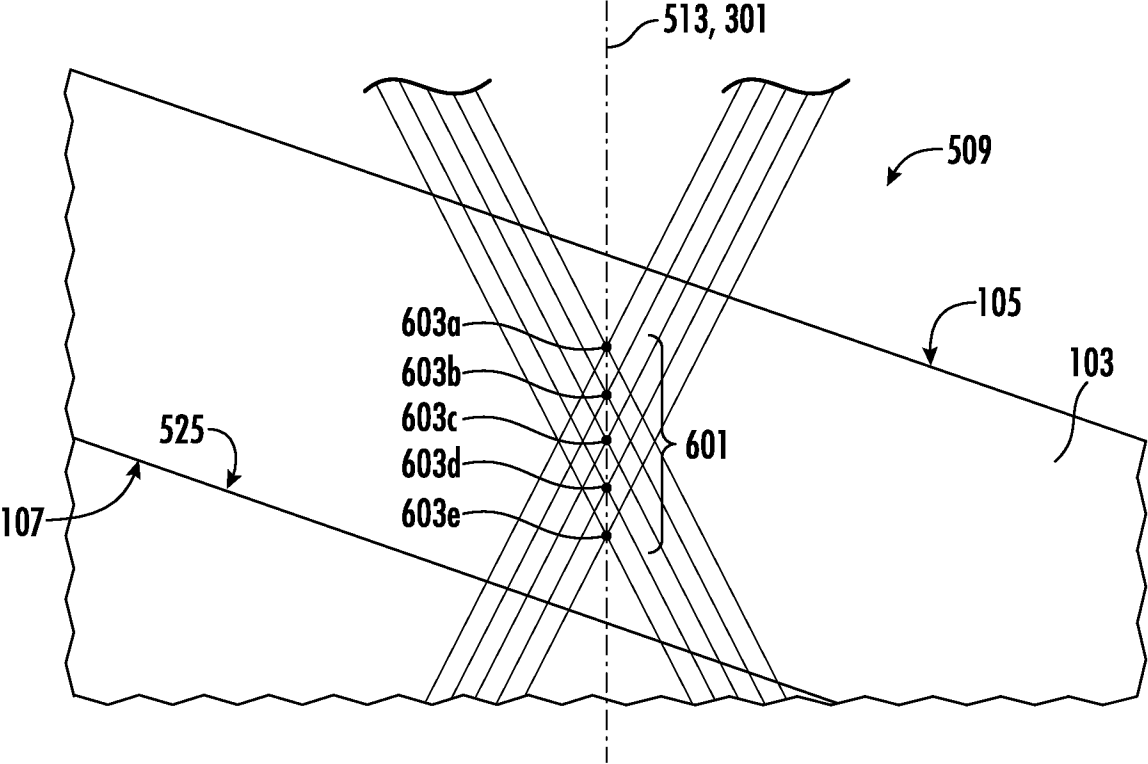


FIG. 6

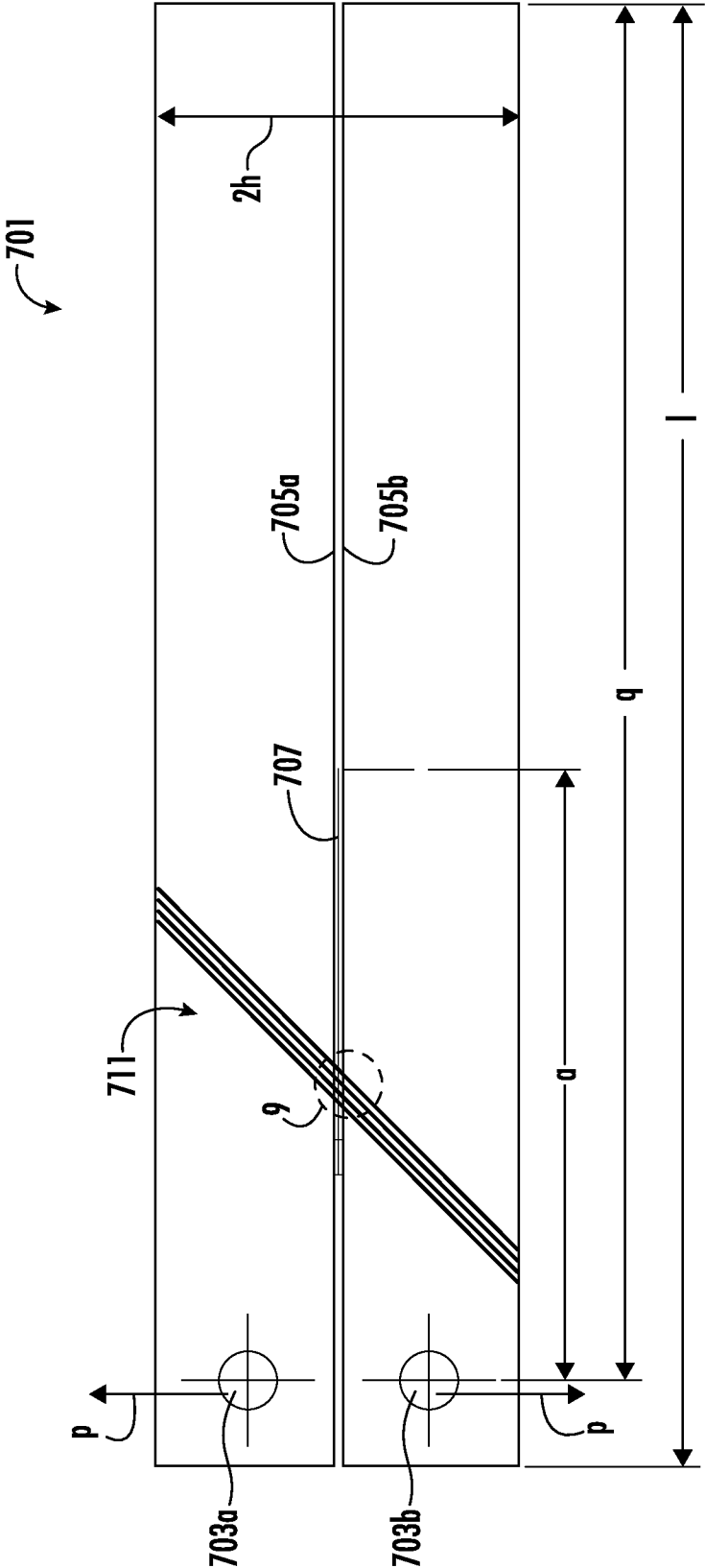


FIG. 7

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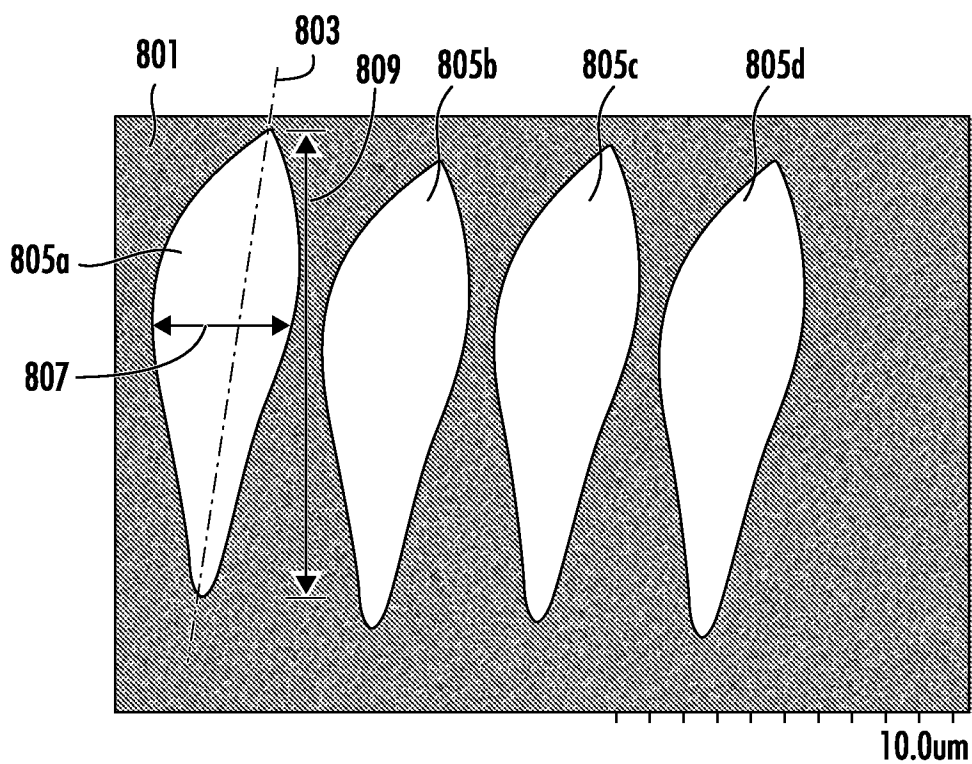


FIG. 8

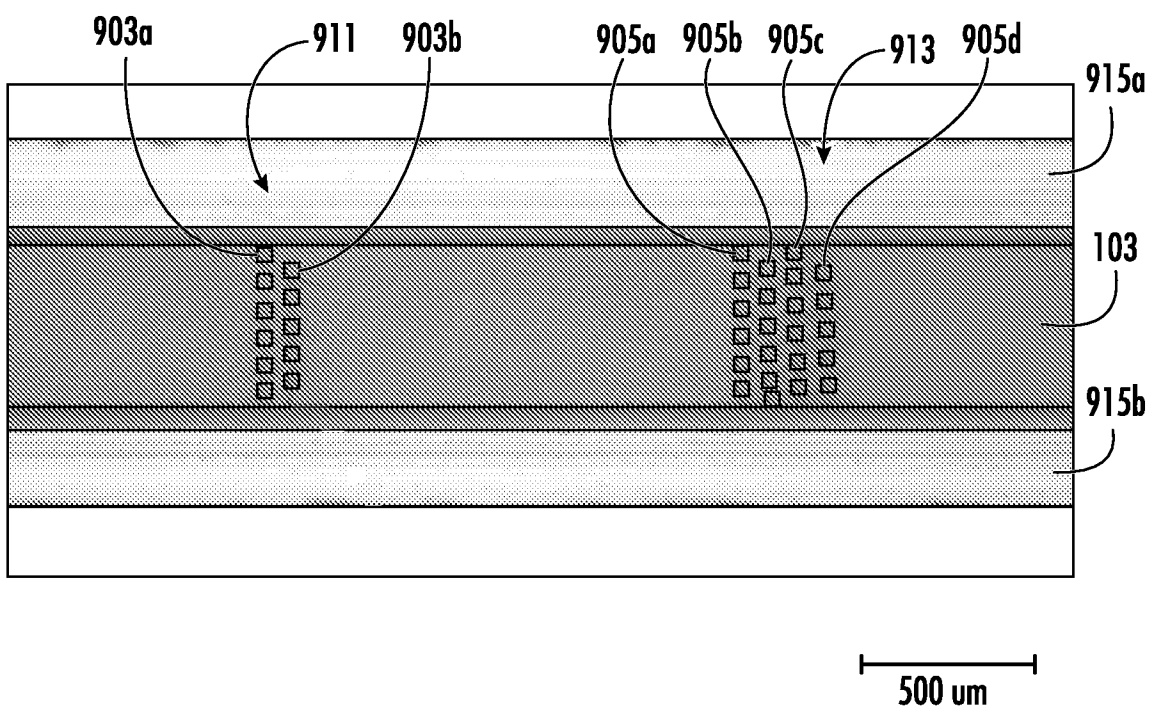


FIG. 9

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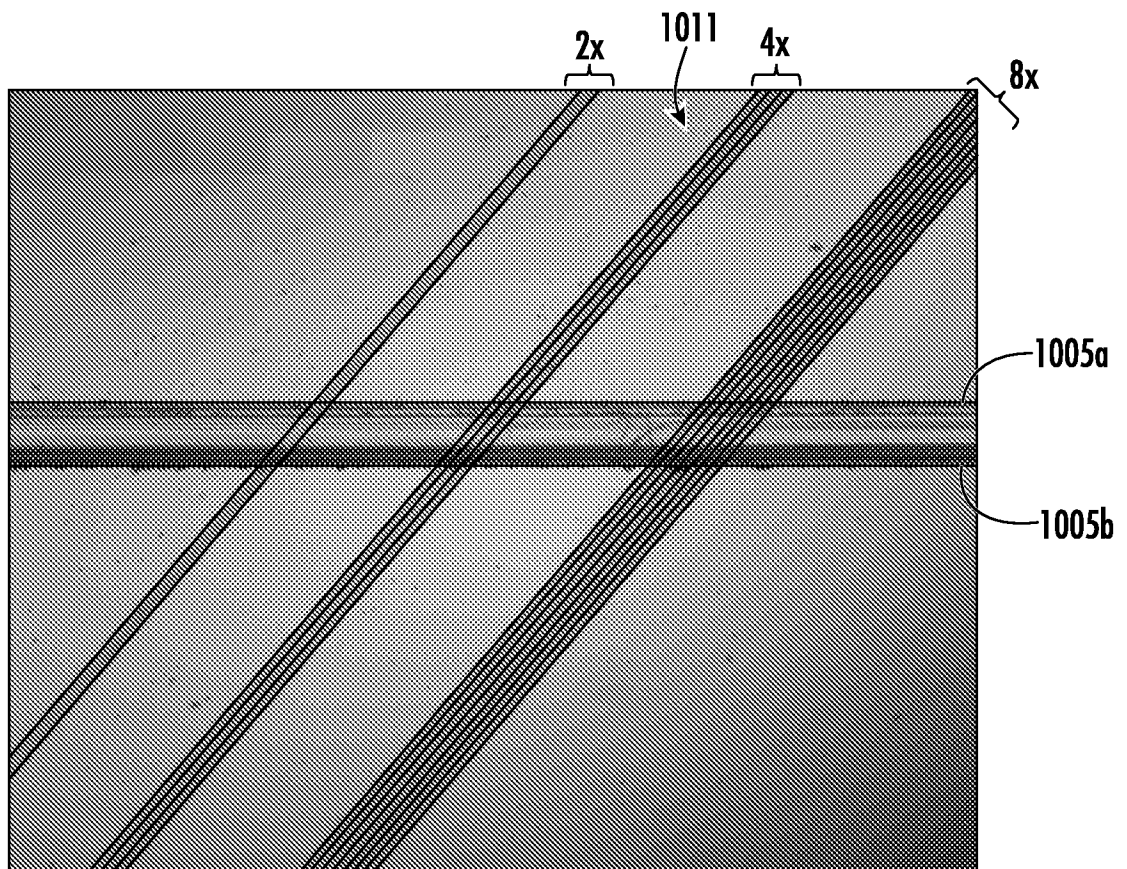


FIG. 10

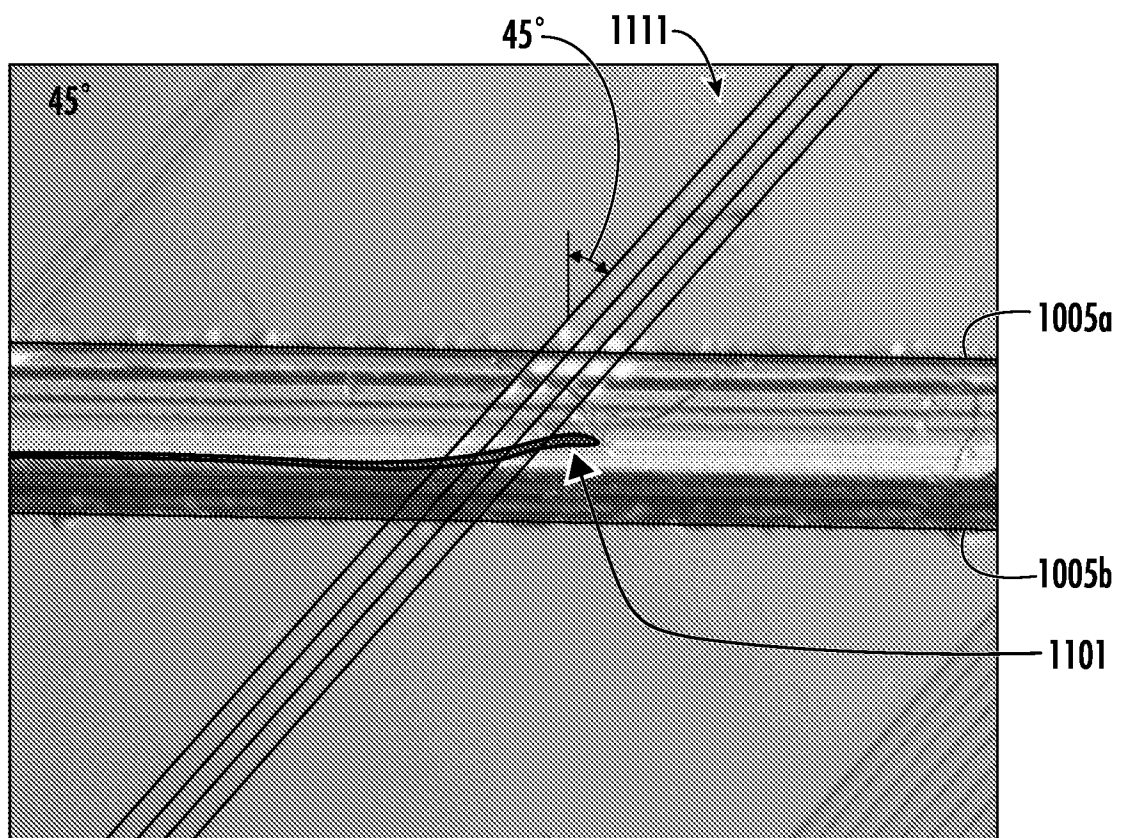


FIG. 11

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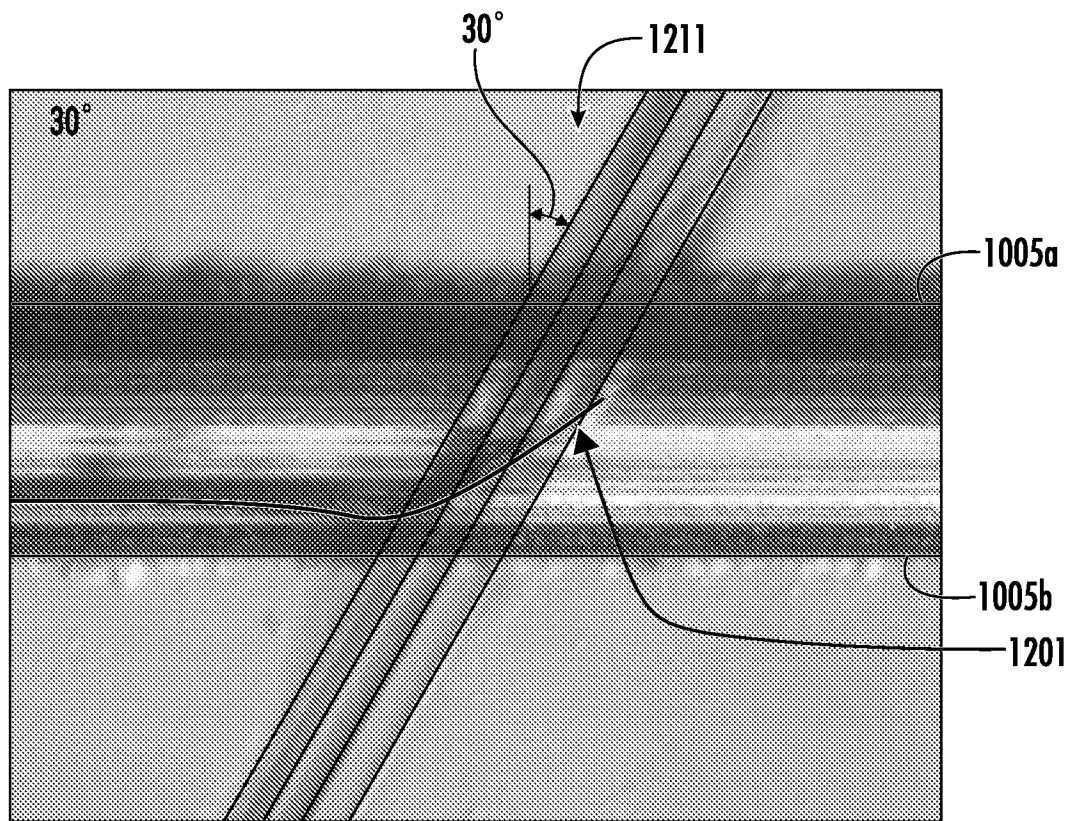


FIG. 12

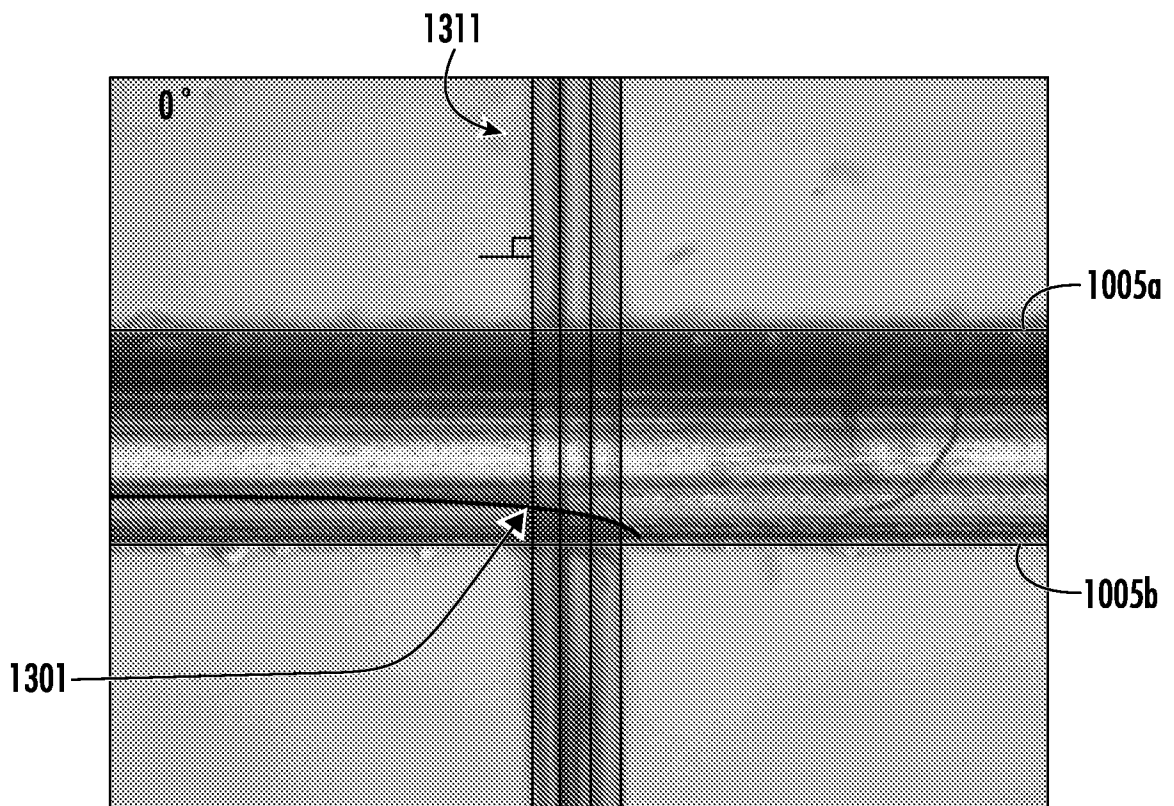


FIG. 13

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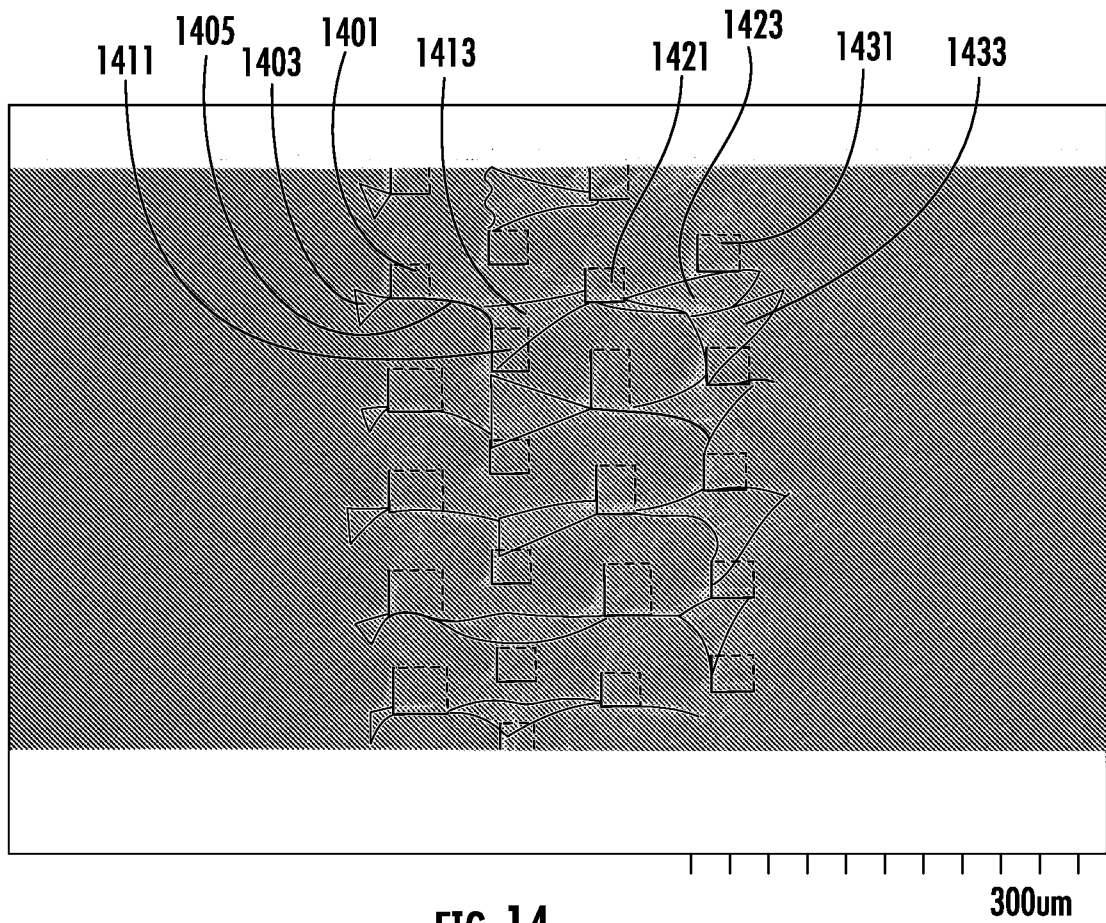


FIG. 14

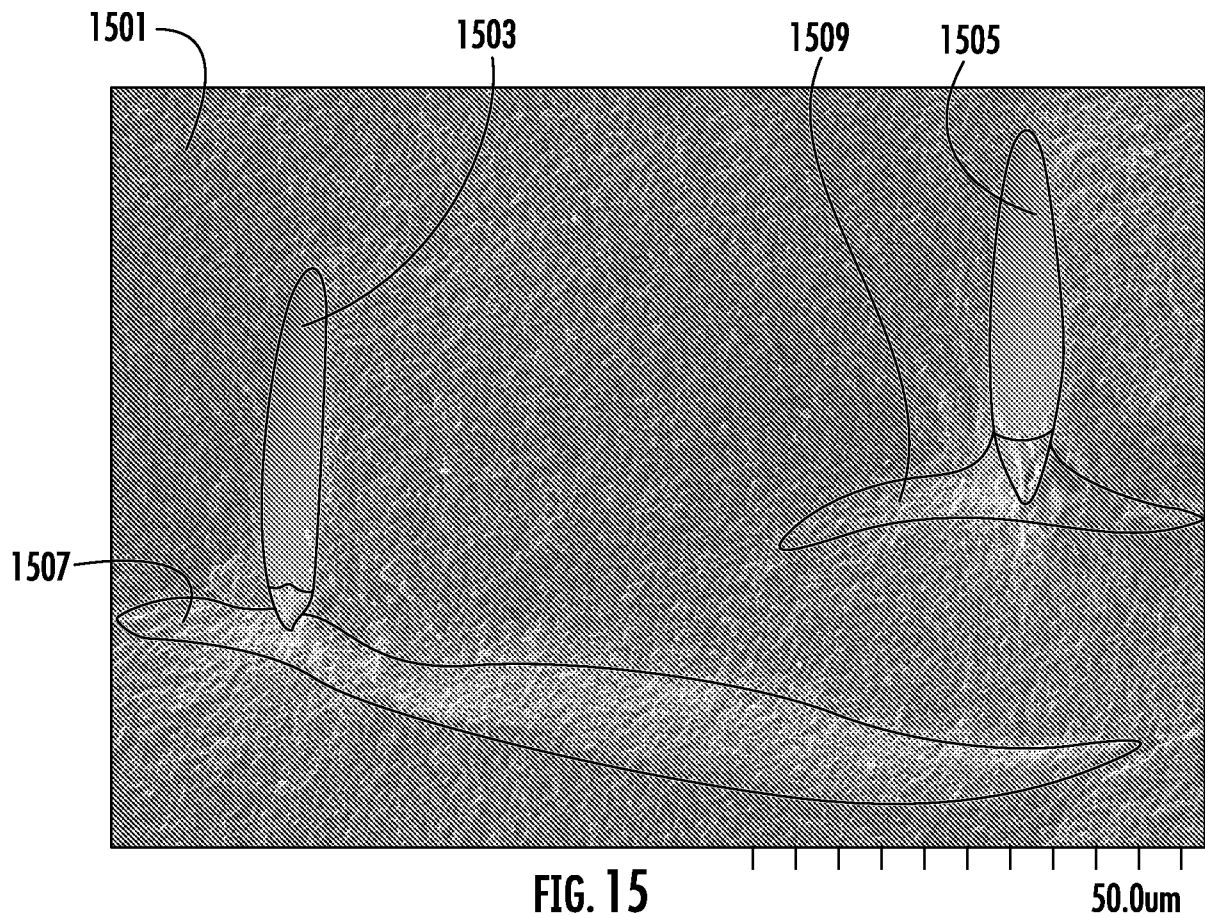


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/055445

A. CLASSIFICATION OF SUBJECT MATTER

INV. C03C3/097 C03C10/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C03C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2022/057561 A1 (LESLIE PATRICK SCOTT [US] ET AL) 24 February 2022 (2022-02-24) paragraphs [0005] - [0006], [0010] - [0019], [0030] - [0050], [0074], [0076] - [0081], [0083] - [0087], [0104] - [0109]; figures 1-6 -----	1 - 29
X	US 10 702 948 B2 (SCHOTT AG [DE]) 7 July 2020 (2020-07-07) column IV, lines 14-36; figure 5a column V, line 16 - column VI, line 11 column VI, line 42 - column VII, line 4 column IX, line 52 - column X, line 9 page XI, lines 52-67 column XII, line 57 - column XIII, line 33 column VX, line 65 - column XVI, line 15 column XVI, line 66 - column XVII, line 12 ----- - / - -	1 - 29



Further documents are listed in the continuation of Box C.



See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

12 February 2025

Date of mailing of the international search report

20/02/2025

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Authorized officer

Lecerf, Nicolas

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2024/055445

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	US 2015/246415 A1 (HOSSEINI S ABBAS [US]) 3 September 2015 (2015-09-03) paragraphs 6-8, 38 - column XVI, line 15; figures 8C, 8D -----	1 - 29

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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