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(54) METHOD FOR TAILORING THE DOPANT PROFILE IN A LASER CRYSTAL USING ZONE PROCESSING

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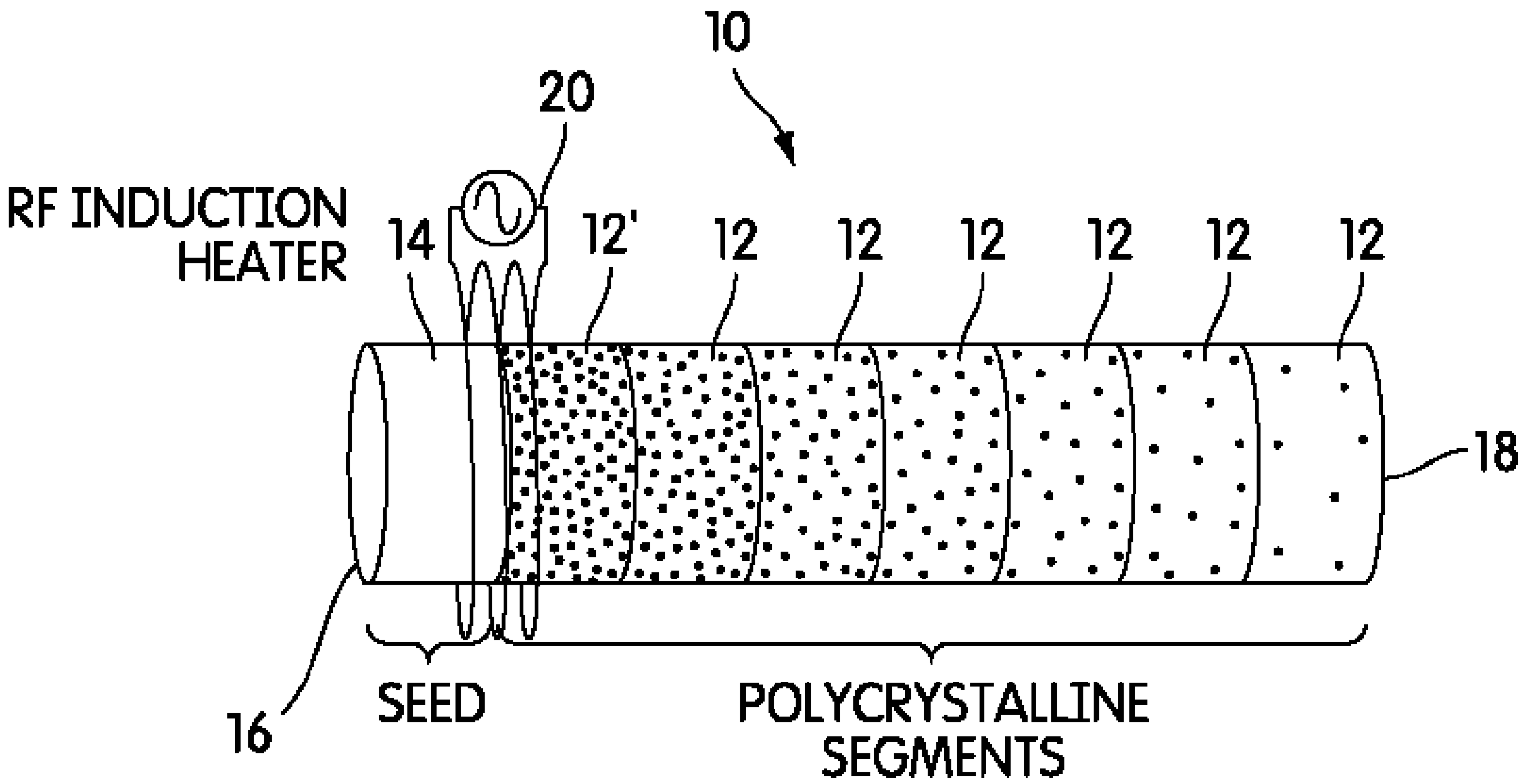
(57) **ABSTRACT**

A lasing medium having a tailored dopant concentration and a method of fabrication thereof is disclosed. The lasing medium has a single crystal having a continuous body having a selected length, wherein the crystal comprises dopant distributed along the length of the body to define a dopant concentration profile. In one embodiment, the dopant concentration profile results in a uniform heating profile. A method of fabricating a laser crystal having a tailored dopant concentration profile includes arranging a plurality of polycrystalline segments together to form an ingot, the polycrystalline segments each having dopant distributed, providing a crystal seed at a first end of the ingot, and moving a heating element along the ingot starting from the first end to a second end of the ingot, the moving heating element creating a moving molten region within the ingot while passing therealong.



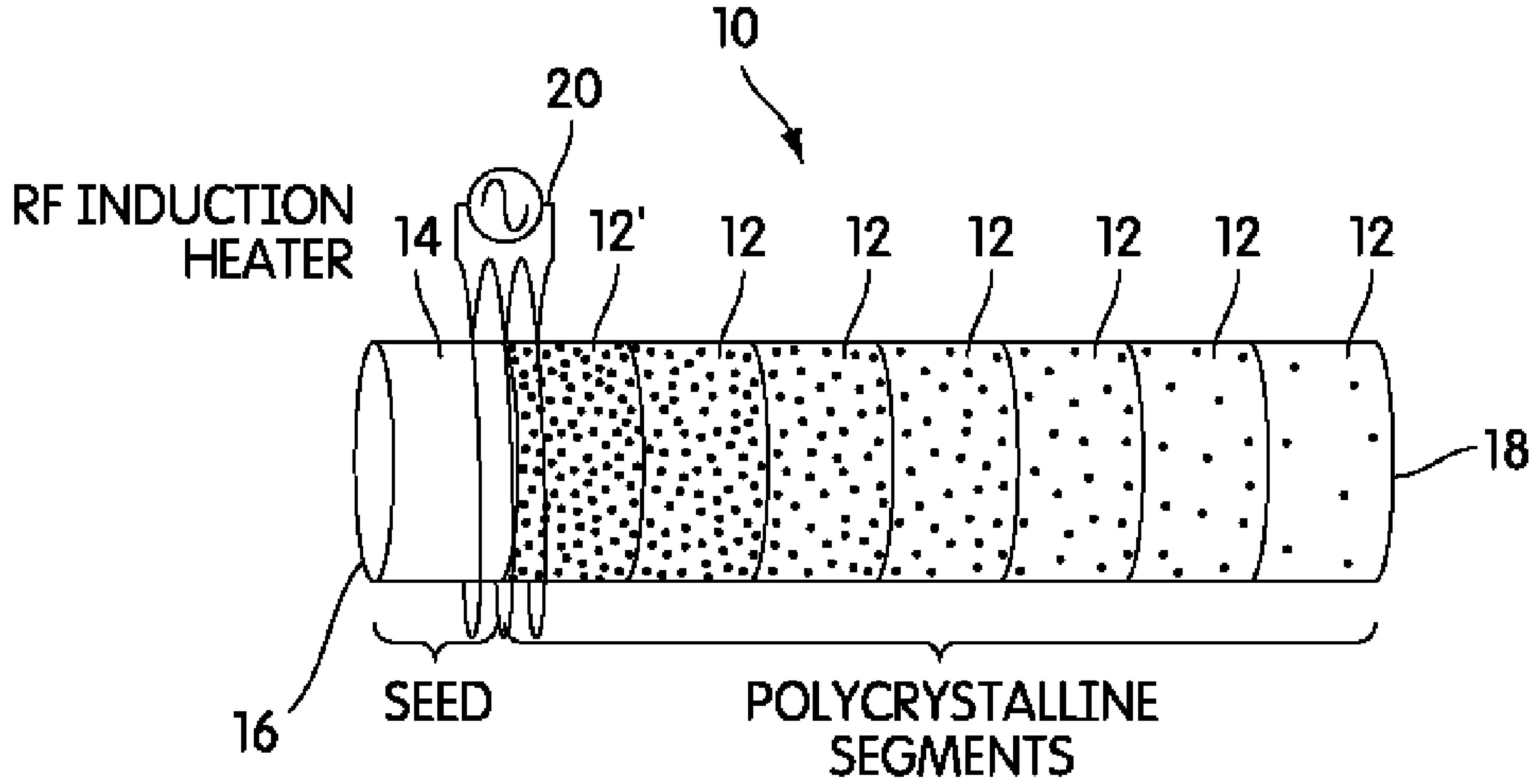

10
20
RF INDUCTION
HEATER
14
12'
12
12
12
12
12
12
18
16
SEED
POLYCRYSTALLINE
SEGMENTS

FIG. 1a

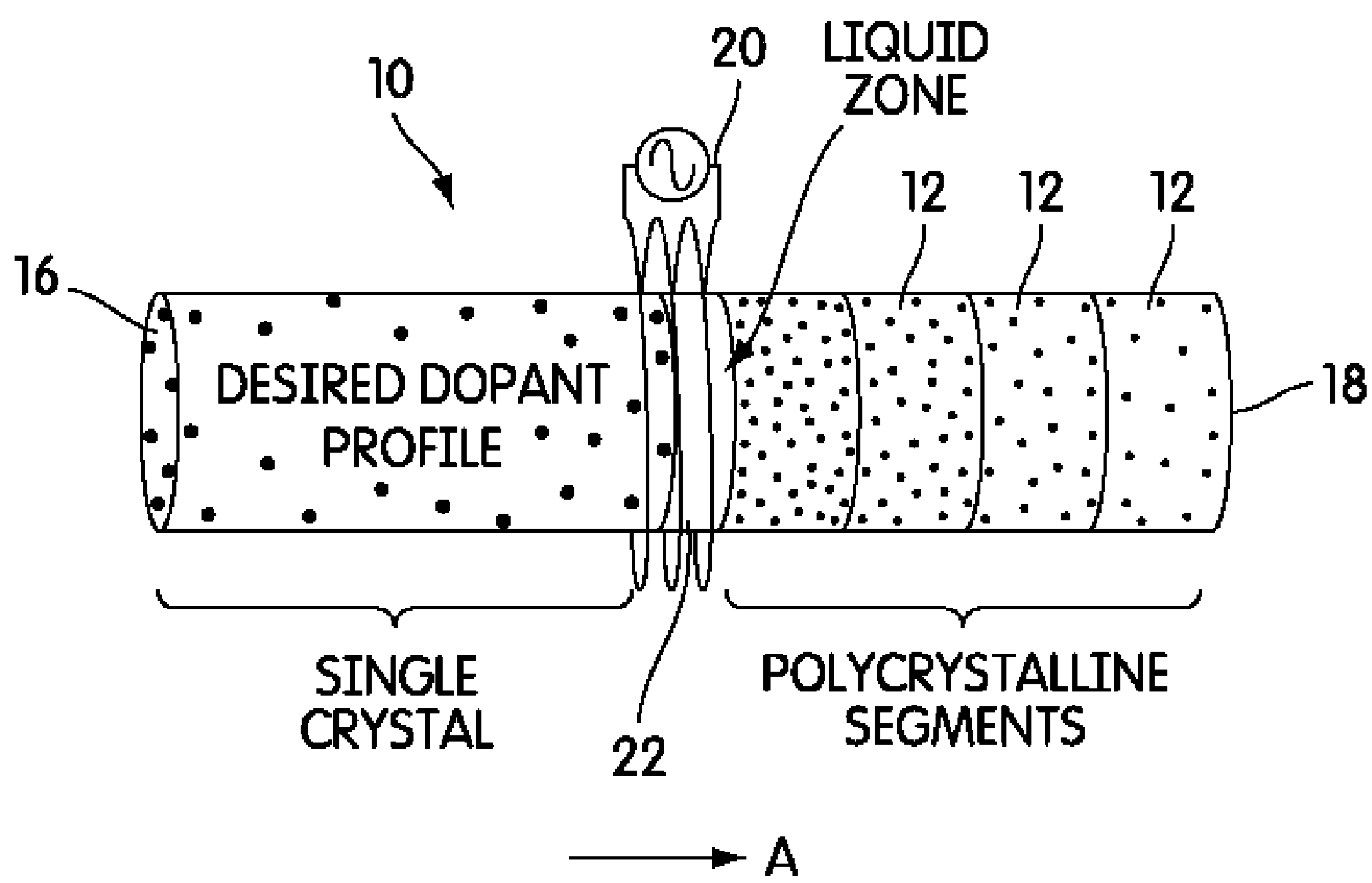

10
20
LIQUID
ZONE
16
12
12
12
DESIRED DOPANT
PROFILE
18
SINGLE
CRYSTAL
22
POLYCRYSTALLINE
SEGMENTS
A

FIG. 1b

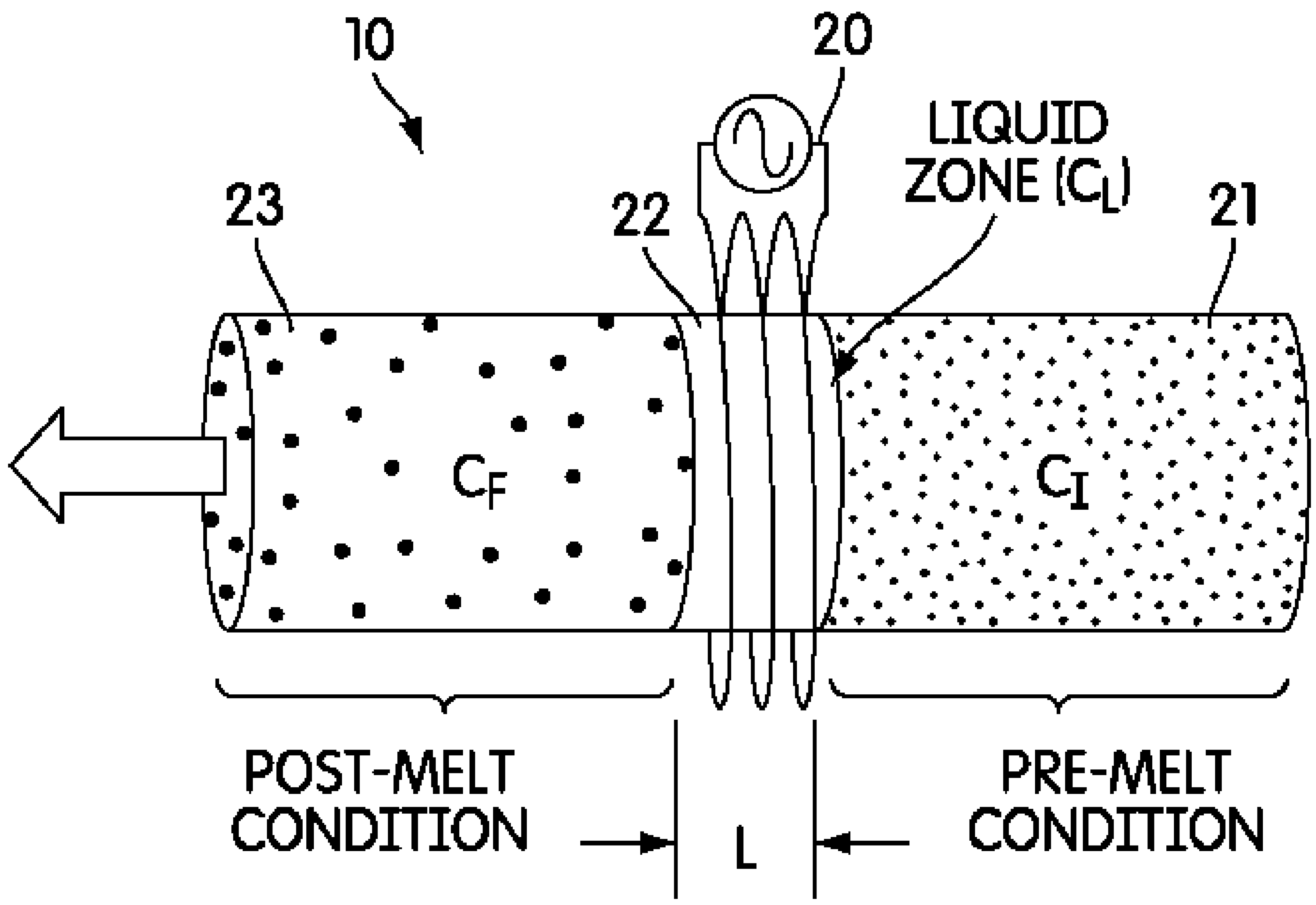

10
20
LIQUID ZONE (C_L)
23
22
21
C_F
C_I
POST-MELT CONDITION
L
PRE-MELT CONDITION

FIG. 2

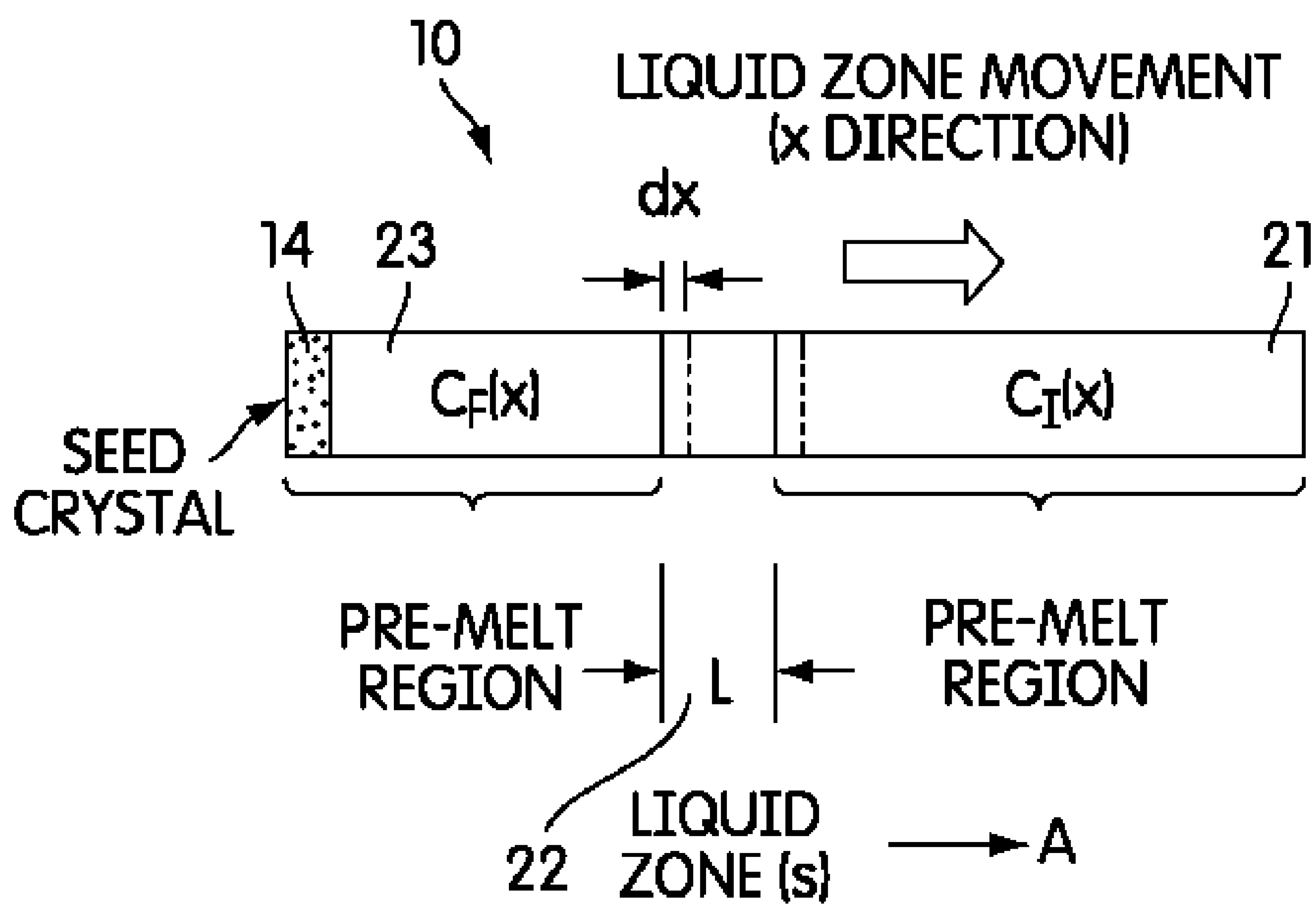

10
LIQUID ZONE MOVEMENT (x DIRECTION)
dx
14
23
21
$C_F(x)$
$C_I(x)$
SEED CRYSTAL
PRE-MELT REGION
L
PRE-MELT REGION
22
LIQUID ZONE (s)
A

FIG. 3

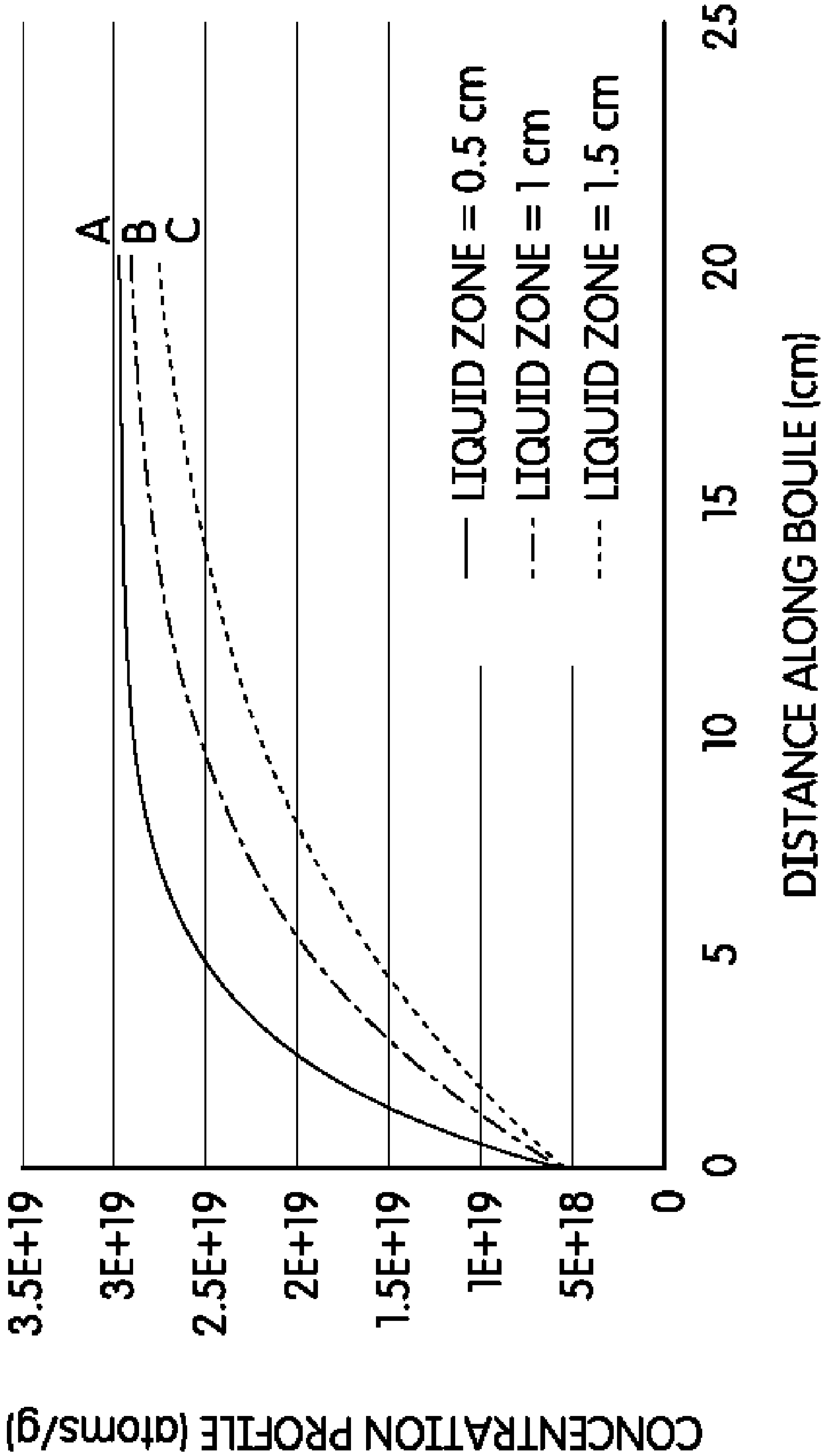

CONCENTRATION PROFILE (atoms/g)
3.5E+19
3E+19
2.5E+19
2E+19
1.5E+19
1E+19
5E+18
0
DISTANCE ALONG BOULE (cm)
0
5
10
15
20
25
A
B
C
LIQUID ZONE = 0.5 cm
LIQUID ZONE = 1 cm
LIQUID ZONE = 1.5 cm

FIG. 4

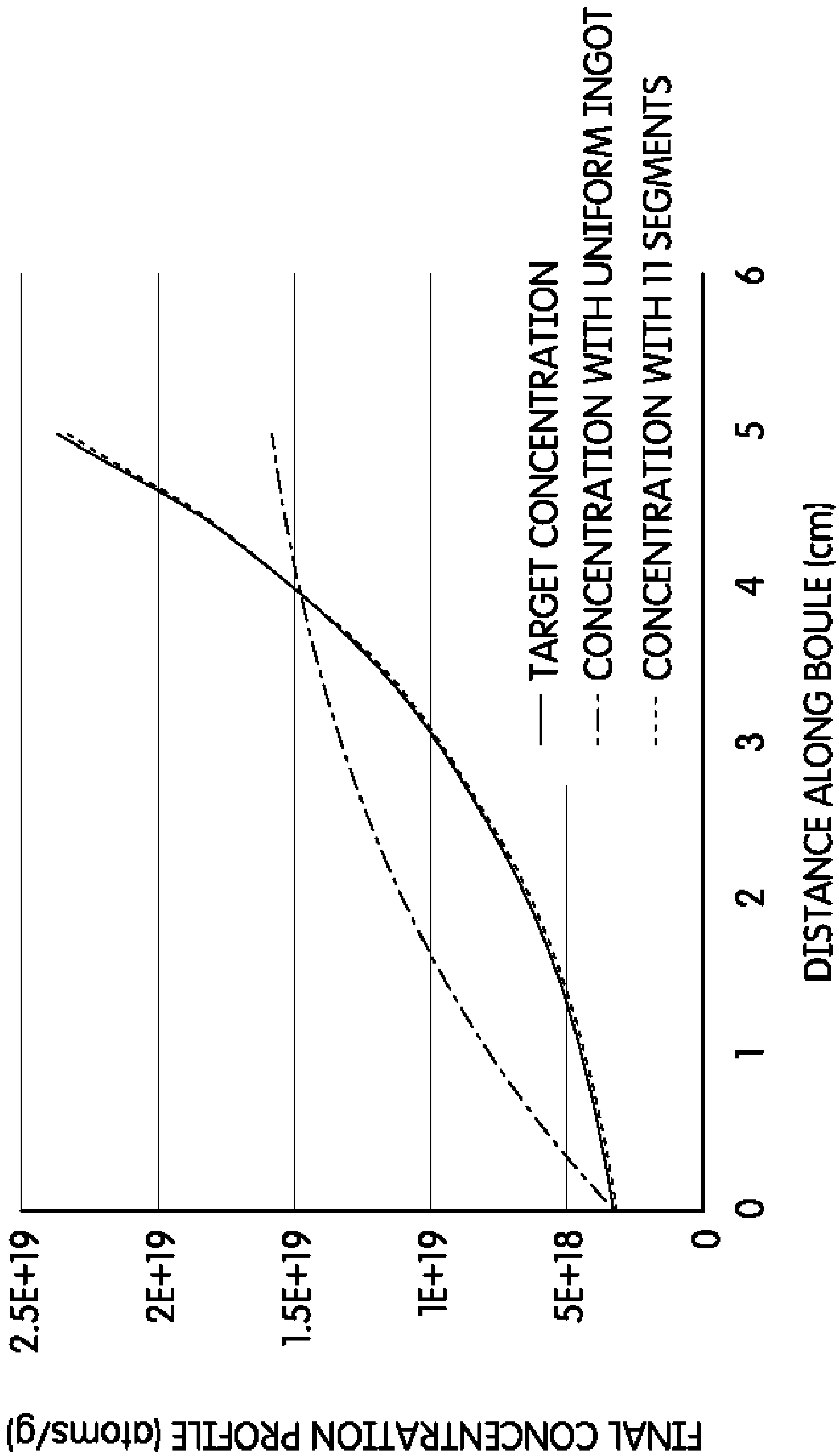

FINAL CONCENTRATION PROFILE (atoms/g)
2.5E+19
2E+19
1.5E+19
1E+19
5E+18
0
0
1
2
3
4
5
6
DISTANCE ALONG BOULE (cm)
TARGET CONCENTRATION
CONCENTRATION WITH UNIFORM INGOT
CONCENTRATION WITH 11 SEGMENTS

FIG. 5

METHOD FOR TAILORING THE DOPANT PROFILE IN A LASER CRYSTAL USING ZONE PROCESSING

BACKGROUND

[0001] The present disclosure relates to solid-state lasers. More specifically, the present disclosure relates to a laser crystal having a tailored dopant profile, the method of fabricating thereof, and a lasing medium fabricated from said laser crystals.

[0002] Solid-state lasers are currently being developed and used for a variety of military and industrial applications, including range finding, target designation/marking, illumination, three-dimensional imaging, vibration sensing, profilometry, cutting, drilling, welding, heat treating and other material processing, electro-optical and infrared countermeasures, and directed energy weapons. A solid-state laser typically includes a laser amplifier medium or lasing medium disposed within an optical resonant cavity. The resonant cavity or resonator provides the feedback necessary to build oscillation of electromagnetic radiation within the laser. The bulk lasing medium is typically in the shape of a slab, rod, or disk. When pumped, the medium provides amplification by a process of stimulated emission. The provision of reflective surfaces or gratings at the ends of the lasing medium provides a resonator.

[0003] In a typical laser, an incoherent light source imparts energy to the lasing medium, which produces light in which the waves are in phase through particular electron transitions. Where the lasing medium is properly designed, this "coherent light" is emitted as a beam.

[0004] Commercial laser gain media typically comprise single crystals having substantially uniform dopant concentration, such as Nd:YAG (neodymium doped yttrium-aluminum-garnet). Developmental lasers are being designed with optical-quality poly-crystalline ceramic lasing media which offer size and cost advantages over conventional single-crystal media. Solid-state lasing media, doped with an active ion, often use one or more flash lamps or laser diodes to provide "pump light." The diode pump light excites the active ions in the doped crystalline or ceramic lasing medium to a higher energy state. This process is known as "absorption." A "pump cavity" typically contains a uniformly doped lasing medium, which may be a crystal or glass or polycrystalline ceramic element fabricated in the shape of a rod, slab, or disk, and other elements, such as a pump light reflector or relay optics. Pump light is coupled into the cavity, typically with one or more flash lamps or laser diodes, either from the side of the cavity (i.e., side pumping) or the end of the cavity (i.e., end pumping).

[0005] Efficient absorption, in which nearly all of the pump light is absorbed by the doped medium, is a primary goal of laser designers. One method of attaining efficient absorption is by using high-absorption (highly doped) laser materials. A ray of pump light going through a doped crystal one time is known as a "pass." With most existing designs, a pump light ray makes only one or two passes through the doped crystal before escaping, necessitating the use of high-absorption materials to achieve efficient absorption. Absorption is governed by an exponential function. Thus, when such a crystal is side-pumped, non-uniform absorption and thus non-uniform gain often result, with the highest gain being near the edge of the lasing medium. The concentration of gain near the edge of the medium leads to problems with parasitic oscillation and amplified spontaneous emission (ASE), extraction, efficiency, and beam quality (mode control). This is particularly problematic with respect to rod shaped media.

[0006] Another approach to the goal of high efficiency absorption uses end pumping, in which pump light comes into a pump cavity along its longitudinal axis. End pumping requires high-brightness pump diodes and durable dichroic coatings, since the pumping and laser light extraction take place through the same optical surfaces (i.e. the ends of the rod) while requiring quite different reflectivity characteristics. In the case of quasi-four level (e.g., ytterbium doped yttrium aluminum garnet, Yb:YAG) or three-level systems (e.g., ruby) where the high threshold requires greater pumping rate, pump "bleaching" can occur, in which a large fraction of the active ions have been excited and correspondingly fewer ions are in the ground state available for pump light absorption, resulting in reduced absorption for both side- and end-pumping geometries.

[0007] A laser crystal having a tailored concentration profile may be especially useful for laser applications which may use a high-aspect-ration slab geometry for the lasing medium. One special case of the slab geometry is the planar waveguide (PWG) which is advantageous for applications requiring high gain, high average power, and high efficiency. As is known in the art, the PWG has a planar geometry, which guides light only in the thin dimension of the slab. For an end-pumped laser, the dopant absorbs the pump energy along the length of the medium and releases it radiatively as photons and non-radiatively as heat. Thus, heat is a function of both the energy pumped into the laser material and the dopant level of the laser material. Accordingly, as the pump energy and/or the dopant concentration are increased, both laser emission and heat generation are increased. Uniform dopant concentration that is typically used in lasing media results in localized heating. This is because the pump energy is absorbed by the dopant and thus decreases as it travels through the lasing medium. Accordingly, the material near the pump light end receives the most energy and produces the most heat, resulting in localized heating. Heat effects may have a negative impact on the laser efficiency and beam quality of high-average-power solid state lasers, and thus composite structure materials such as bonded crystals and composite ceramics have been used to mitigate the heat effects.

[0008] To achieve constant heating throughout the lasing medium, a tailored longitudinal concentration profile (of active ion dopant) is needed. Lasing media with different concentrations along the length thereof have been used. For example, multiple single crystal segments each having a different concentration are bonded together to form a lasing medium with a stepped dopant concentration profile. However, these lasing media are bonded at interfaces that cross the laser beam axis, resulting in media that are more expensive to fabricate and prone to damage. Alternatively, there are lasing media having a concentration profile that is created by mixing ultra-fine powders of different concentrations along the laser axis of the body. The structure is then sintered to form a dense, optically clear ceramic. However, these media may not exhibit the same superior lasing performance as a pristine single crystal.

[0009] What is needed is a method and apparatus that addresses one or more of the deficiencies noted above in fabricating lasing media having a tailored dopant concentration profile.

SUMMARY

[0010] One embodiment of this disclosure provides a method of fabricating a single, contiguous laser crystal having a tailored dopant concentration profile. The method includes arranging a plurality of polycrystalline segments together to form an ingot. The polycrystalline segments each have dopant distributed therein. The method further includes providing a crystal seed at a first end of the ingot and moving a heating element along the ingot starting from the first end to a second end of the ingot. The moving heating element creates a moving molten region within the ingot while passing therealong.

[0011] Another embodiment provides a single crystal having a tailored dopant concentration profile, produced by a process that includes the steps of arranging a plurality of polycrystalline segments together to form an ingot. The polycrystalline segments each have dopant distributed therein. The steps also include providing a crystal seed at a first end of the ingot and moving a heating element along the ingot starting from the first end to a second end of the ingot. The moving heating element creates a moving molten region within the ingot while passing therealong.

[0012] Another embodiment provides a lasing medium that includes a single crystal having a continuous body having a selected length, wherein the crystal comprises dopant distributed along the length of the body to define a dopant concentration profile that results in a uniform heating profile. The lasing medium may be produced by machining the single crystal using processes known in the art such as core drilling, saw cutting, grinding, polishing, and coating to produce a final lasing medium with a desired shape and optical characteristics.

[0013] These and other features and characteristics of the present disclosure, as well as the methods of operation and functions of the related elements of structure and the combination of parts and economies of manufacture, will become more apparent upon consideration of the following description and the appended claims with reference to the accompanying drawings, all of which form a part of this specification, wherein like reference numerals designate corresponding parts in the various figures. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only and are not intended as a definition of the limits of the inventive concept. As used in the specification and in the claims, the singular form of "a", "an", and "the" include plural referents unless the context clearly dictates otherwise.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] In the accompanying drawings:

[0015] FIG. **1***a* illustrates a starting ingot formed from a plurality of polycrystalline segments;

[0016] FIG. **1***b* illustrates a heating element passing through the ingot and creating a liquid zone therein during float zone processing;

[0017] FIG. **2** illustrates a liquid zone and post-melt and pre-melt regions of the ingot during float zone processing;

[0018] FIG. **3** schematically depicts the liquid zone and the post-melt and pre-melt regions of the ingot during float zone processing and identifies the parameters used in corresponding mathematical equations;

[0019] FIG. **4** is a plot of a final concentration profile for a laser crystal;

[0020] FIG. **5** is a plot of comparisons between a target concentration, a concentration profile resulting from float zone processing performed on a uniform ingot, and a concentration profile resulting from float zone processing performed on multiple segments having different dopant concentrations.

DETAILED DESCRIPTION

[0021] Lasing media can be fabricated to have a tailored dopant concentration profile. In some embodiments, the lasing media includes an elongated, single crystal having a continuous body having a selected length. The crystal may include dopant distributed along the length of the body and may have a dopant concentration profile in accordance with a target dopant concentration profile.

[0022] The lasing medium may be fabricated using float zone processing or zone melting. Float zone processing has been used in the semiconductor industry to purify crystals by melting a narrow region of the crystal. This molten zone is then moved along an ingot by moving a heating element along the longitudinal axis of the crystal. As the molten region moves through the ingot, this molten region melts impure solids and leaves behind a single crystal region of purer materials as it solidifies. As a result, the impurities concentrate in the melt, and are moved to one end of the ingot. The purifying process works on the principle that, since the segregation coefficient k, which is the ratio of an impurity in the solid phase to that in the liquid phase, is usually less than one, the impurity atoms will diffuse to the liquid region at the solid/liquid boundary. Thus, by passing a crystal boule through a thin section of furnace very slowly, such that only a small region of the boule is molten at any time, the impurities may be segregated at the end of the crystal.

[0023] FIGS. **1***a*-**1***b* illustrates using float zone processing to tailor the concentration of active lasing species (or dopants) within a laser crystal. As known in the art, dopants are typically inserted into a substance in order to alter the electrical properties or the optical properties of the substance. In the case of crystalline substances, the atoms of the dopant commonly take the place of elements that were in the crystal lattice of the material. For example, YAG, which is also known as yttrium aluminum garnet ($Y_3Al_5O_{12}$), is a popular synthetic crystal material that is usually doped with some element to form a laser crystal. The yttrium ions in YAG can be replaced with laser-active rare earth ions (e.g., neodymium) up to some concentration limit without strongly affecting the lattice structure. The concentration limit is determined by size of the dopant ion (e.g., neodymium) relative to that of the substituted ion (e.g., yttrium). These dopant ions may essentially carry out the lasing process in the crystal. The other atoms in the crystal (i.e., the yttrium, aluminum, and oxygen atoms) support the dopant atoms and provide a crystal field that influences the energy band structure of the laser. A variety of crystal materials may be used, for example, $Y_3Al_5O_{12}$, $YLiF_4$, or $Gd_3Ga_5O_{12}$. A variety of dopants may also be used, just for example, ytterbium, erbium, thulium, or holmium.

[0024] As shown in FIG. **1***a*, starting ingot **10** is formed from plurality of polycrystalline segments **12**. The starting ingot may be oriented such that its longitudinal axis is vertical. In one embodiment, each polycrystalline segment **12** has a different dopant concentration from the other segments. However, it is contemplated that segments **12** may have the same dopant concentration or alternatively may be a single polycrystalline segment. It should be appreciated that the number of segments **12** may vary in other embodiments. The length of each segment **12** and the concentration in each segment **12** may also vary to achieve the target concentration profile. Segments **12** may be vertically stacked without bonding or sintering and held in place only by gravity. Single seed crystal **14** may be provided at first end **16** of ingot **10** and arranged with segments **12** to form ingot **10**. Seed crystal **10** may be substantially pure or doped with a concentration of dopant. Seed crystal **14** lattice orientation is the same as the desired orientation of the resulting lasing crystal. Ingot **10** may also include a second end **18** opposite first end **16**. Heating element **20** may be used to form liquid zone **22**. In one embodiment, ingot **10** is oriented such that its longitudinal axis is vertical with seed crystal at the top, the end of seed crystal not adjacent to a polycrystalline segment is clamped or bonded to a holding fixture to offset the force of gravity, and heating element **20** is moved vertically from top to bottom while ingot **10** is held stationary. The starting location of heating element **20** is near the interface between the seed crystal **14** and the adjacent polycrystalline segment **12'** such that end **16** of seed crystal **14** remains a crystallized solid and defines the crystal structure and lattice orientation of the resulting lasing crystal. Heating element **20** may be provided by RF induction or any other methods or apparatuses. Just for example, in some embodiments, heating element **20** may be induction coils, ring-wound resistance heaters, or gas flames. In one embodiment, ingot **10** may be heated radiatively using an induction-heated tungsten ring. In some embodiments wherein ingot **10** is electrically conductive an electric current may be passed through the ingot while it is suspended in a magnetic field with the current controlled such that the material is magnetically levitated to minimize gravity sag in the liquid zone **22**.

[0025] The liquid zone **22** formed by heating element **20** may similar to the "molten zone" described above with respect to purification of crystals. Liquid zone **22** moves through ingot **10** and disperses the dopants through ingot **10** to form the dopant concentration profile. FIG. **1***b* shows heating element **20** moving through ingot **10** in the direction of A, and thus moving liquid zone **22** through ingot **10**. As heating element **20** moves liquid zone **22** through ingot **10**, a resulting crystal portion **24** having the desired concentration profile is formed.

[0026] Seed crystal **14** and each segment **12** of ingot **10** may be doped with a selected active lasing species, which behaves as the "impurity" in the float zone purification process described above. However, rather than refining the ingot, the process of FIG. **1** produces a single crystal having a desired or target one-dimensional dopant profile. The resulting profile may be achieved by selecting the proper dopant concentration within each segment **12** such that the natural diffusion of active lasing species within the liquid zone and the difference in solubility of active lasing species between solid and liquid phases results in the desired profile. The difference in solubility of active lasing species between solid and liquid phases which gives rise to the lowering of concentration in the single crystal region is characterized by the segregation coefficient for the particular dopant within the particular crystal. In some embodiments, seed crystal **14** should be doped with the same concentration as desired at first end **16** of the resulting crystal and segments **12** near seed crystal **14** that will be melted first should have a higher concentration of dopant than the target concentration. In such embodiments, segments **12** closer to second end **18** of ingot **10** may have less concentration of dopant. Thus, in the embodiment shown in FIG. **1***a*, the concentrations of segments **12** are decreasing from first end **16** to second end **18**. The smoothness of the doping profile may depend on the steepness of the desired concentration gradient and the number of polycrystalline segments **12** in ingot **10**.

[0027] FIG. **2** shows an expanded view of the region around liquid zone **22** where the dopant species are mixed within the liquid during melting. Region **21** represents a pre-melt region or condition and has a concentration of C_I. C_I represents the initial concentration of dopant species by weight. C_I can be a constant if a single uniformly-doped segment is used. Alternatively, if multiple segments **12** having different dopant concentrations are used, C_I may be a function of distance along the length of ingot **10** in the direction of A. Region **23** represents the post-melt region or condition having a concentration of C_F. C_F represents the final concentration, which is a function of distance along the length of the resulting crystal. It should be appreciated that multiple segments **12** may be used and their lengths and concentrations tailored to give a final concentration profile. For example, the final concentration of the resulting crystal may be tailored by varying the length of each polycrystalline segment, varying the concentration of the dopant in each polycrystalline segment, varying the length of the liquid zone, varying the number of passes that the heating element is moved along the ingot, and varying other factors that will be described below. Accordingly, C_I represents the pre-melt condition and C_F represents the post-melt condition.

[0028] Float zone processing that is performed on polycrystalline segments **12** can convert polycrystalline lasing material to a single crystal where a standard growth process (e.g., Czochralski growth process) is impossible, impractical from a size standpoint, and/or results in unwanted stress regions within the crystal. For example, neodymium-doped YAG formed by the Cazochralski growth process has a stressed region formed along the center of the crystal that is not useable for lasing media. In contrast, the resulting crystal formed by the float zone processing of multiple polycrystalline segments **12** has a continuous body, a tailored dopant concentration profile along the length of the body, and no substantially stressed regions. The resulting crystal may be a single crystal with the identical crystal structure and lattice orientation as crystal seed **14** and a concentration profile that can be arbitrarily tailored with precision by varying any of the factors or parameters described below.

[0029] FIG. **3** shows the same region as FIG. **2** and shows the parameters used to analyze the doping profile. The parameters are defined as below:

[0030] L=length of liquid zone

[0031] x=distance along ingot

[0032] $C_I(x)$=concentration (by weight) of the starting ingot

[0033] $C_F(x)$=concentration (by weight) of final laser crystal

[0034] s=amount of dopant present in liquid zone at a given location

[0035] A=cross section area of ingot

[0036] k=segregation coefficient (ratio of dopant concentration in solid to that in liquid across solidus/liquidus interface)

[0037] ρ=specific gravity of solid crystal

[0038] The molten region (liquid zone **22** shown in FIGS. **1***a*, **1***b*) propagates from left to right in the direction of A as heater **20** is moved accordingly. As liquid zone **22** advances by an infinitesimal distance, dx, the amount of dopant added to liquid zone **22** from the ingot is $C_I(x)A\rho dx$. The amount of dopant removed from liquid zone **22** at the retreating crystal interface is (ks/L)dx. Therefore, the net addition of dopant to liquid zone **22** when zone **22** advances by dx is $ds=[C_I(x)A\rho-(ks/L)]dx$.

[0039] The boundary condition at the seed crystal end is $s(0)=C_I(0)AL\rho$. The concentration of the final crystal boule is given by $C_F(x)=ks/(AL\rho)$. If the starting ingot has uniform doping (C_I=constant), then the differential equations can be solved explicitly, yielding an exponentially increasing value of $C_F(x)$ given by $C_F(x)=C_I[1-(1-k)\exp(-kx/L)]$.

[0040] The above equations can be solved for any given concentration profile for the polycrystalline ingot. That is, to tailor the concentration profile, the above equations may be used to determine the value of the parameters. Alternatively, the input values of the parameters may be used to determine the resulting concentration profile.

[0041] In one embodiment, the resulting lasing medium is neodymium-doped yttrium aluminum garnet (Nd:YAG). Nd:YAG offers substantial laser gain even for moderate excitation levels and pump intensities. The gain bandwidth may be relatively small, but this allows for a high gain efficiency and thus low threshold pump power. The segregation coefficient for neodymium in YAG (k=0.18) is very low due to the poor fit of the neodymium ion as a substitute impurity in the yttrium lattice site. This low value, however, produces a substantial concentration gradient in the float zone process, which may be desirable for certain end-pumping applications. The area of the ingot might not be a factor in the analysis, but the interfaces between the solid and the liquid phases should be relatively flat and normal to the direction of A. This may prevent or minimize a lateral component to the concentration gradient, which may not be desirable. However, the resulting crystal may have features or performance characteristics that vary based on the float zone processing apparatuses, the physical and thermal design of the laser pump head, and the handling and thermal robustness of laser crystal **12**.

[0042] In one embodiment, the crystal may have the following parameters:

[0043] L=0.5 cm, 1 cm, 1.5 cm

[0044] $\rho=4.56$ g/cm^3

[0045] $C_I(0)$=1 atomic percent=1.36×10^{20} Nd atoms/cm^3=2.98×10^{19} Nd atoms/g

[0046] k=0.18

[0047] FIG. **4** plots the final concentration profile for a laser crystal with the above parameters. That is, FIG. **4** plots the final concentration profile for laser crystal **12** for several liquid zone lengths after a single pass of heating element **20** along the length of the starting ingot that was doped at 1 atomic percent neodymium. In particular, FIG. **4** shows the concentration profiles for crystals having liquid zone lengths of 0.5 cm, 1 cm, and 1.5 cm. Plot A shows the concentration profile for crystals having liquid zone length of 0.5 cm, plot B shows the concentration profile for crystals having liquid zone length of 1 cm, and plot C shows the concentration profile for crystals having liquid zone length of 1.5 cm. The mass density is 4.56 g/cm^3. The starting amount of neodymium dopant ($C_I(0)$) may be one atomic percent (1.36×10^{20} Nd atoms/cm^3=2.98×10^{19} Nd atoms/g). The segregation coefficient of neodymium in YAG is 0.18.

[0048] FIG. **5** shows a comparison of a resulting crystal having a final concentration produced by using multiple segments of different concentrations versus the resulting crystal having a final concentration produced by a simple float zone process with a uniformly doped starting ingot **10**. The target concentration shown in this Figure represents a near-optimal concentration profile for a small 5 cm long laser crystal designed to be the active layer of a high aspect ratio PWG slab structure. The resultant concentration profile for the uniformly-doped ingot is also shown in FIG. **5**, where the starting concentration of the ingot (1.95×10^{19} atoms/g) is tailored to give the same final concentration as the target profile at the lean end (3.32×10^{18} atoms/g). The resultant concentration for the segmented ingot is also shown where each segment is 0.5 cm long and has the following concentration:

[0049] Segment 1: 1.8×10^{19} atoms/g

[0050] Segment 2: 6.0×10^{18} atoms/g

[0051] Segment 3: 8.0×10^{18} atoms/g

[0052] Segment 4: 9.5×10^{18} atoms/g

[0053] Segment 5: 1.2×10^{19} atoms/g

[0054] Segment 6: 1.6×10^{19} atoms/g

[0055] Segment 7: 1.8×10^{19} atoms/g

[0056] Segment 8: 2.3×10^{19} atoms/g

[0057] Segment 9: 3.1×10^{19} atoms/g

[0058] Segment 10: 3.7×10^{19} atoms/g

[0059] Segment 11: 4.8×10^{19} atoms/g

[0060] In some embodiments, the extra segment at the end may be sacrificed to allow the float zone to pass through the entire useful region of the slab without discontinuity. As shown in FIG. **5**, the concentration profile produced by float zone processing on multiple segments of different dopant concentrations as described above is closer to the target concentration than the concentration produced by a simple float zone process on a uniformly doped starting ingot **10**. Accordingly, the dopant concentration profile of a single crystal may be tailored by performing float zone processing on a plurality of polycrystalline segments.

[0061] As mentioned above, uniformly doped lasing media may result in the material in the pump end receiving the most energy and producing the most heat, thus resulting in localized heating. However, the tailored dopant levels within the single crystal produced by the float zone processing described above may result in uniform heating and uniform laser emission throughout the crystal. That is, the tailored dopant profile of the single crystal may result in a strong, robust lasing medium having a uniform heating profile that can produce higher output power.

[0062] The above description has been provided for the purpose of illustration based on what are currently considered to be the most practical implementations, but it is to be understood that such detail is solely for that purpose, and that the inventive concept is not limited to the disclosed embodiments, but, on the contrary, is intended to cover modifications and equivalent arrangements that are encompassed by the appended claims. For example, it is to be understood that the present disclosure contemplates that, to the extent possible, one or more features of any embodiment can be combined with one or more features of any other embodiment.

[0063] Furthermore, since numerous modifications and changes will readily occur to those with skill in the art, it is not desired to limit the inventive concept to the exact construction and operation described herein. Those with skill in the art may discover other advantages of and applications for the inventive concept in the manufacture of solid-state lasers and other fields without departing from the spirit and scope of this invention.

What is claimed is:

1. A method of fabricating a single, continuous laser crystal having a tailored dopant concentration profile, the method comprising:

arranging a plurality of polycrystalline segments together to form an ingot, the polycrystalline segments each having dopant distributed therein;

providing a crystal seed at a first end of the ingot;

moving a heating element along the ingot starting from the first end to a second end of the ingot, the moving heating element creating a moving molten region within the ingot while passing therealong.

2. The method of claim **1**, wherein the dopant comprises neodymium, ytterbium, erbium, holmium, or a combination thereof.

3. The method of claim **1**, wherein the heating element uses RF induction.

4. The method of claim **1**, wherein each of the segments has a different dopant concentration from other segments.

5. The method of claim **1**, wherein each of the segments has a different length.

6. The method of claim **1**, wherein the seed crystal comprises a dopant concentration equal to a target concentration at the first end of the ingot.

7. The method of claim **1**, wherein a segment at the first end of the ingot has a higher dopant concentration than a segment at the second end of the ingot.

8. The method of claim **1**, wherein moving the heating element along the ingot comprises the heating element surrounding a portion of a length of the ingot.

9. The method of claim **1**, wherein interfaces between the moving molten region and the segments of the ingot are substantially normal to the axis.

10. The method of claim **1**, wherein the crystal comprises YAG ($Y_3Al_5O_{12}$), YLF ($YLiF_4$), GGG ($Gd_3Ga_5O_{12}$).

11. A lasing medium comprising:

a single crystal having a continuous body having a selected length, wherein the crystal comprises dopant distributed along the length of the body to define a dopant concentration profile.

12. The lasing medium of claim **11**, wherein the dopant concentration profile results in a substantially uniform heating profile.

13. The lasing medium of claim **11**, wherein the laser crystal is fabricated with the method of claim **1**, and wherein the laser crystal is machined to a final size.

14. The lasing medium of claim **13**, wherein the laser crystal is machined using saw cutting, core drilling, grinding, polishing, coating, or a combination thereof.

15. The lasing medium of claim **11**, wherein the dopant comprises neodymium, ytterbium, erbium, holmium, or a combination thereof.

16. The lasing medium of claim **11**, wherein the crystal is YAG ($Y_3Al_5O_{12}$), YLF ($YLiF_4$), or GGG ($Gd_3Ga_5O_{12}$).

17. The lasing medium of claim **11**, wherein the lasing medium is in the shape of a rod or slab or configured as a planar waveguide.

18. The lasing medium of claim **11**, wherein the dopant concentration is a function of distance along the length of the crystal.

19. A single crystal having a tailored dopant concentration profile, produced by a process comprising the steps of:

arranging a plurality of polycrystalline segments together to form an ingot, the polycrystalline segments each having dopant distributed therein;

providing a crystal seed at a first end of the ingot;

moving a heating element along the ingot starting from the first end to a second end of the ingot, the moving heating element creating a moving molten region within the ingot while passing therealong.

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