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(54) **OPTICAL GAIN MATERIALS FOR HIGH ENERGY LASERS AND LASER ILLUMINATORS AND METHODS OF MAKING AND USING SAME**

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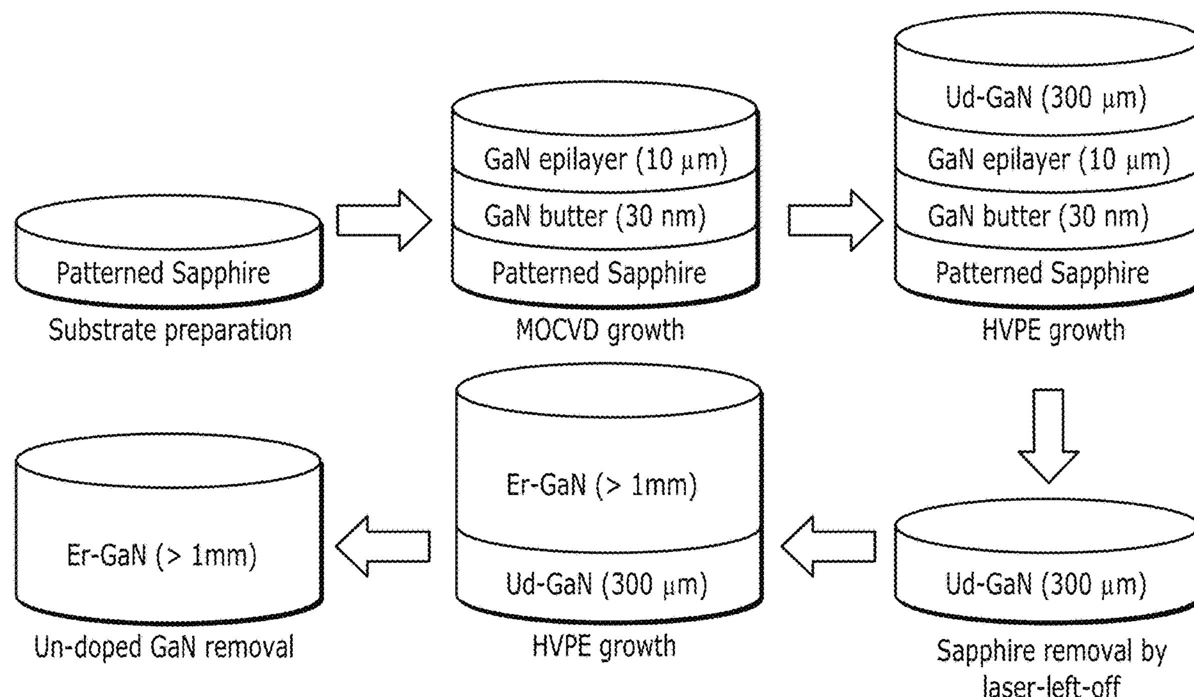
(57) **ABSTRACT**

Core-cladding planar waveguide (PWG) structures and methods of making and using same. The core-cladding PWG structures can be synthesized by hydride vapor phase epitaxy and processed by mechanical and chemical-mechanical polishing. An Er doping concentration of [Er] between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3 can be in the core layer. Such PWGs have a core region that can achieve optical confinement between 96% and 99% and above.



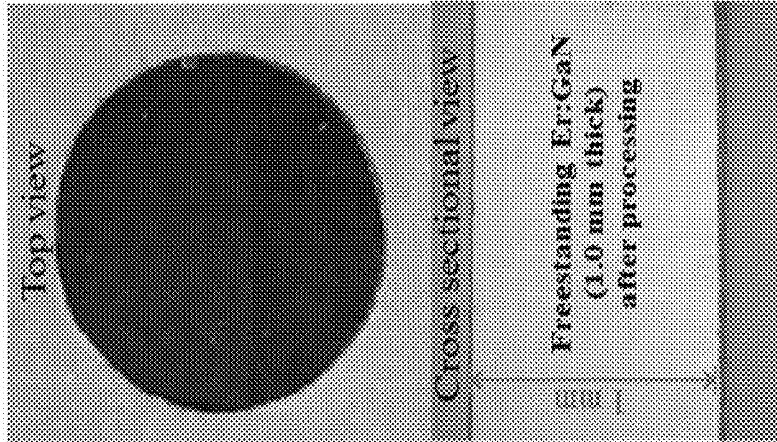


FIG. 1B

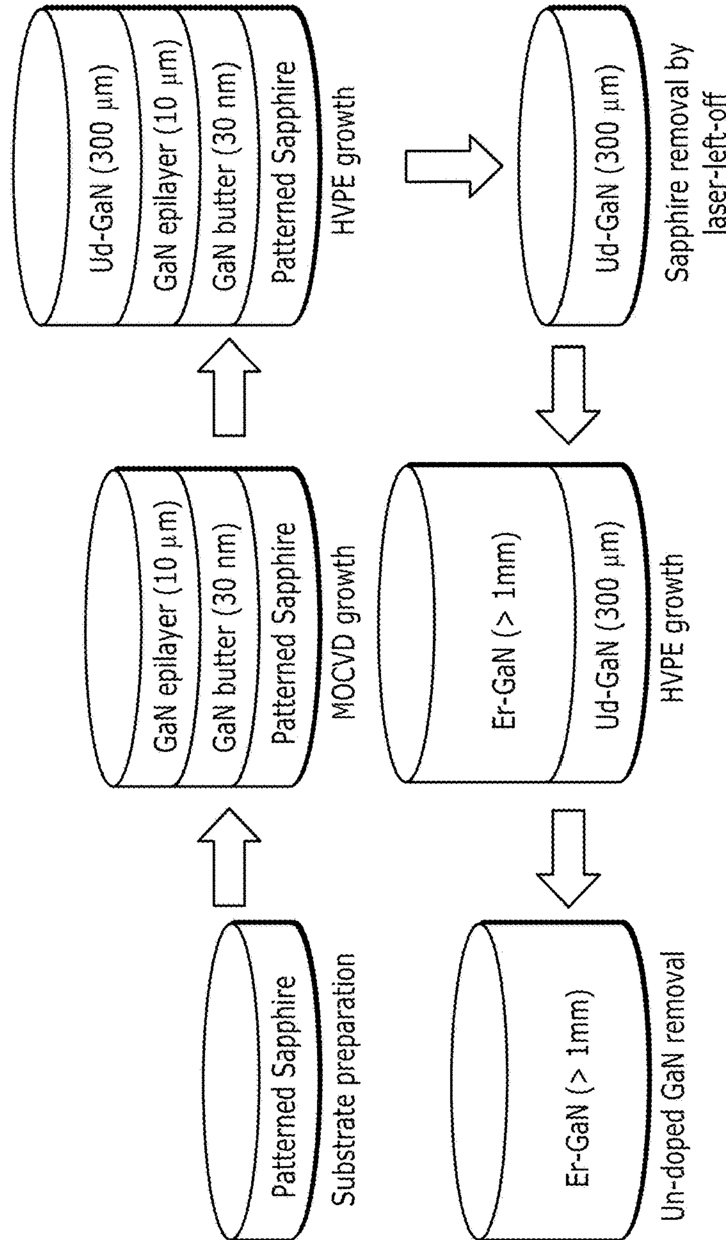


FIG. 1A

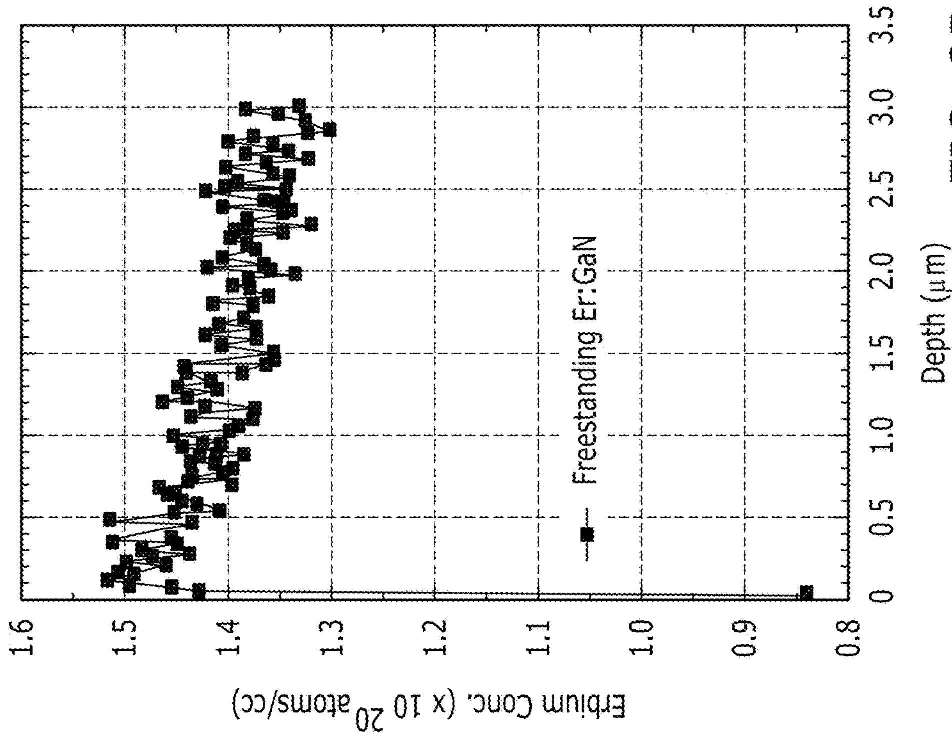


FIG. 2B

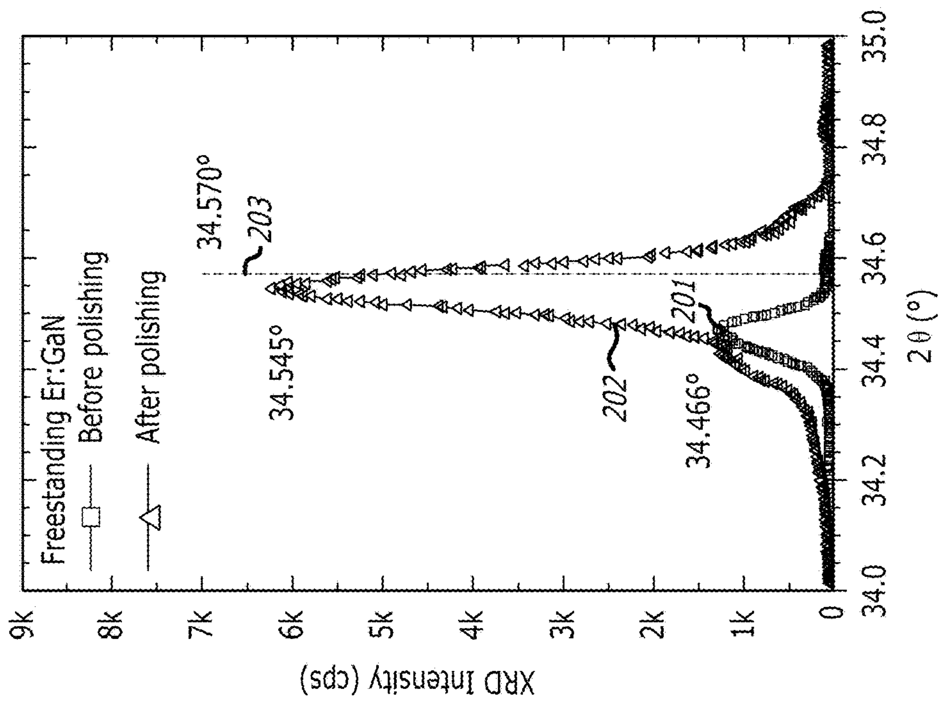


FIG. 2A

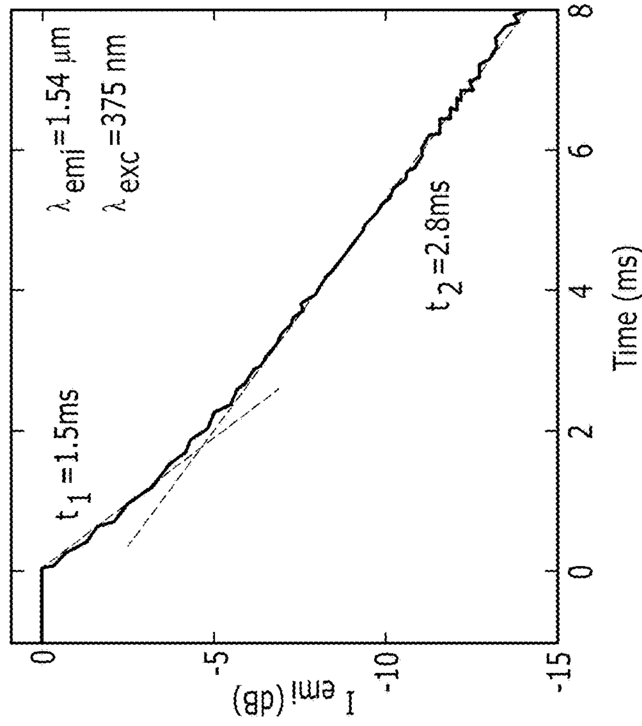


FIG. 3C

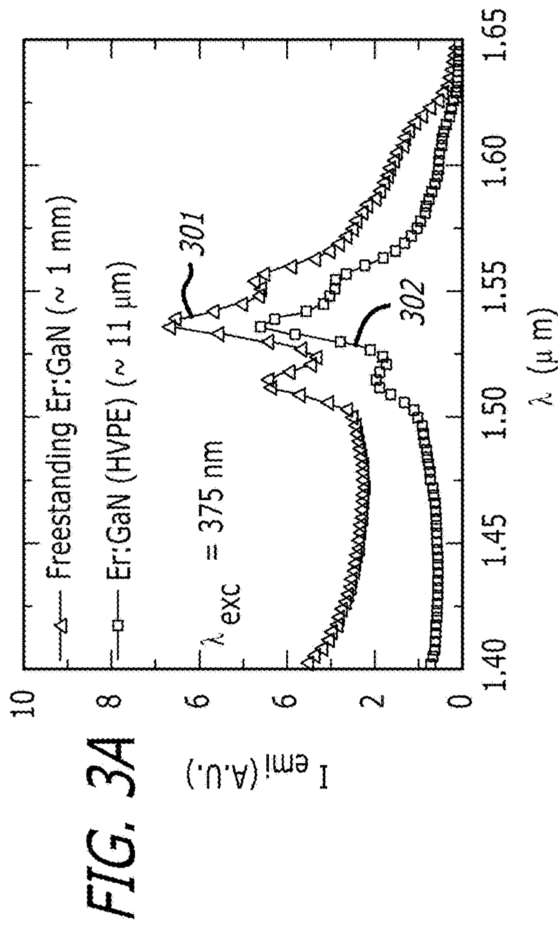


FIG. 3A

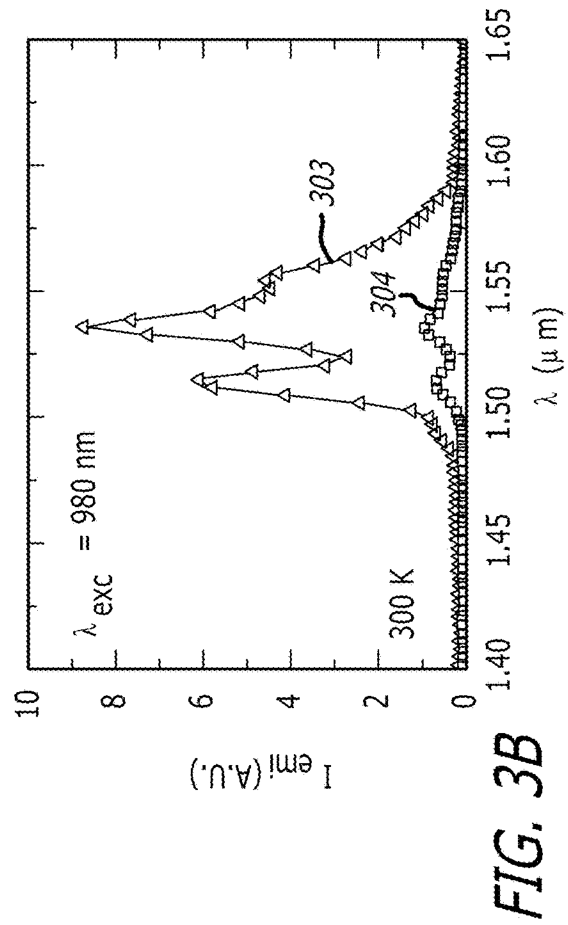


FIG. 3B

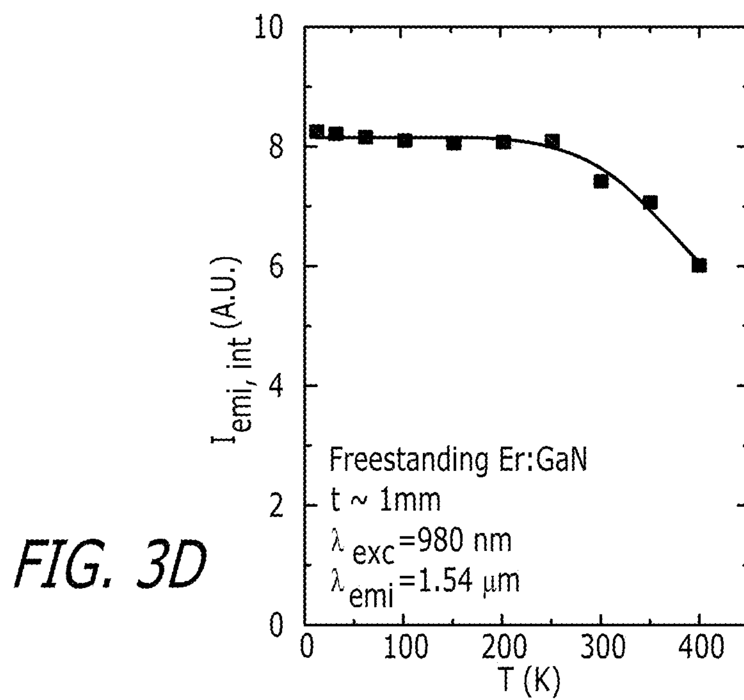


FIG. 3D

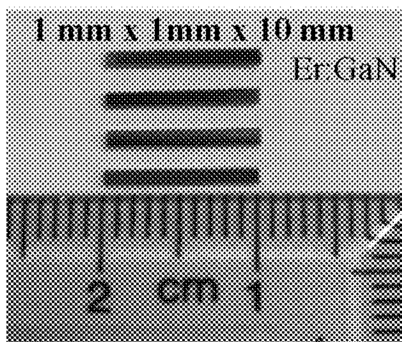


FIG. 4A

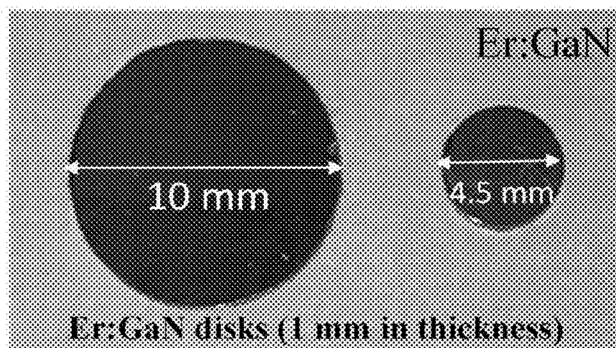


FIG. 4B

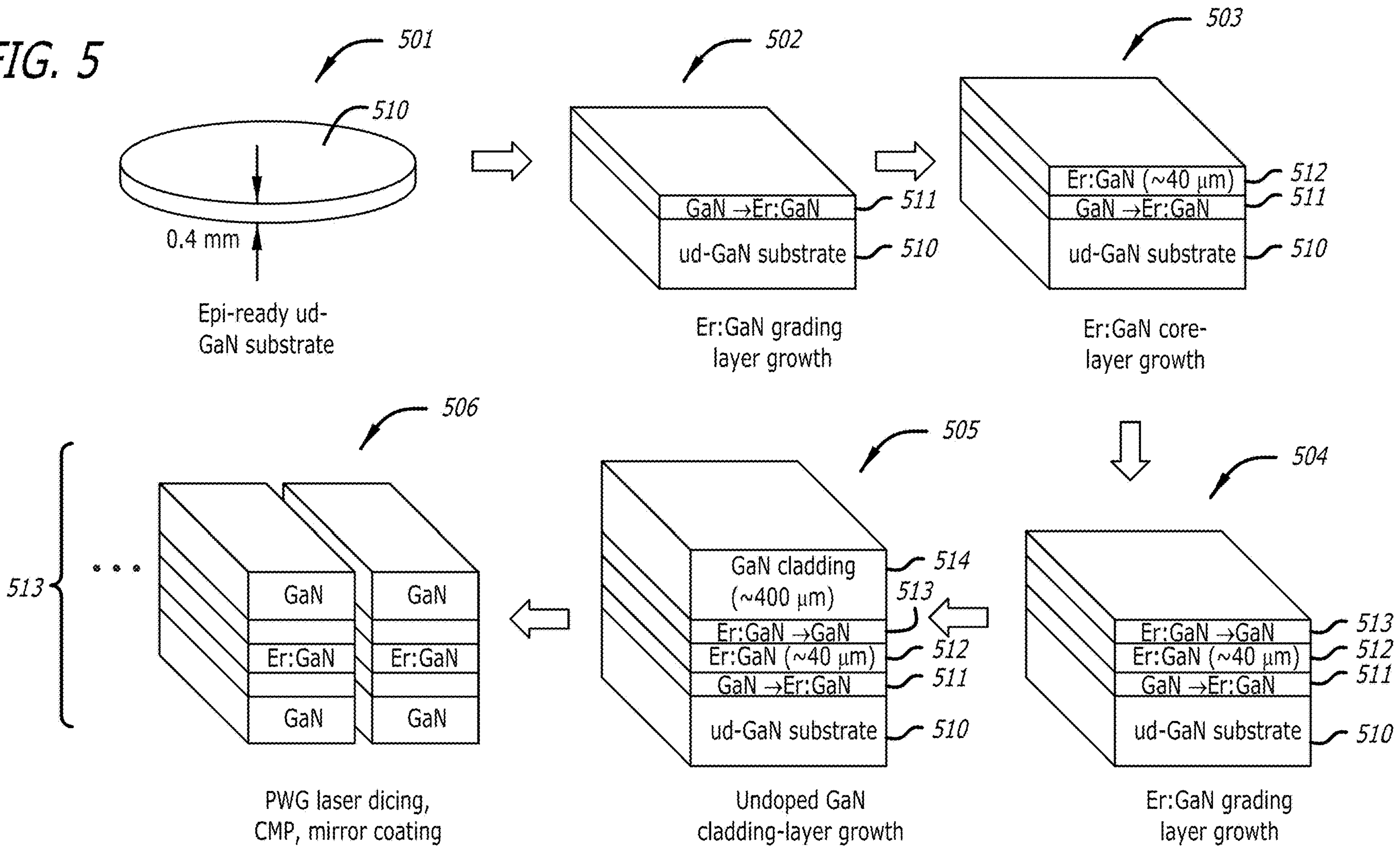


FIG. 5
501
510
0.4 mm
Epi-ready ud-GaN substrate
502
GaN →Er:GaN
ud-GaN substrate
511
510
Er:GaN grading layer growth
503
Er:GaN (~40 μm)
GaN →Er:GaN
ud-GaN substrate
512
511
510
Er:GaN core-layer growth
504
Er:GaN →GaN
Er:GaN (~40 μm)
GaN →Er:GaN
ud-GaN substrate
513
512
511
510
Er:GaN grading layer growth
505
GaN cladding (~400 μm)
Er:GaN →GaN
Er:GaN (~40 μm)
GaN →Er:GaN
ud-GaN substrate
514
513
512
511
510
Undoped GaN cladding-layer growth
506
GaN
Er:GaN
GaN
GaN
Er:GaN
GaN
513
PWG laser dicing, CMP, mirror coating

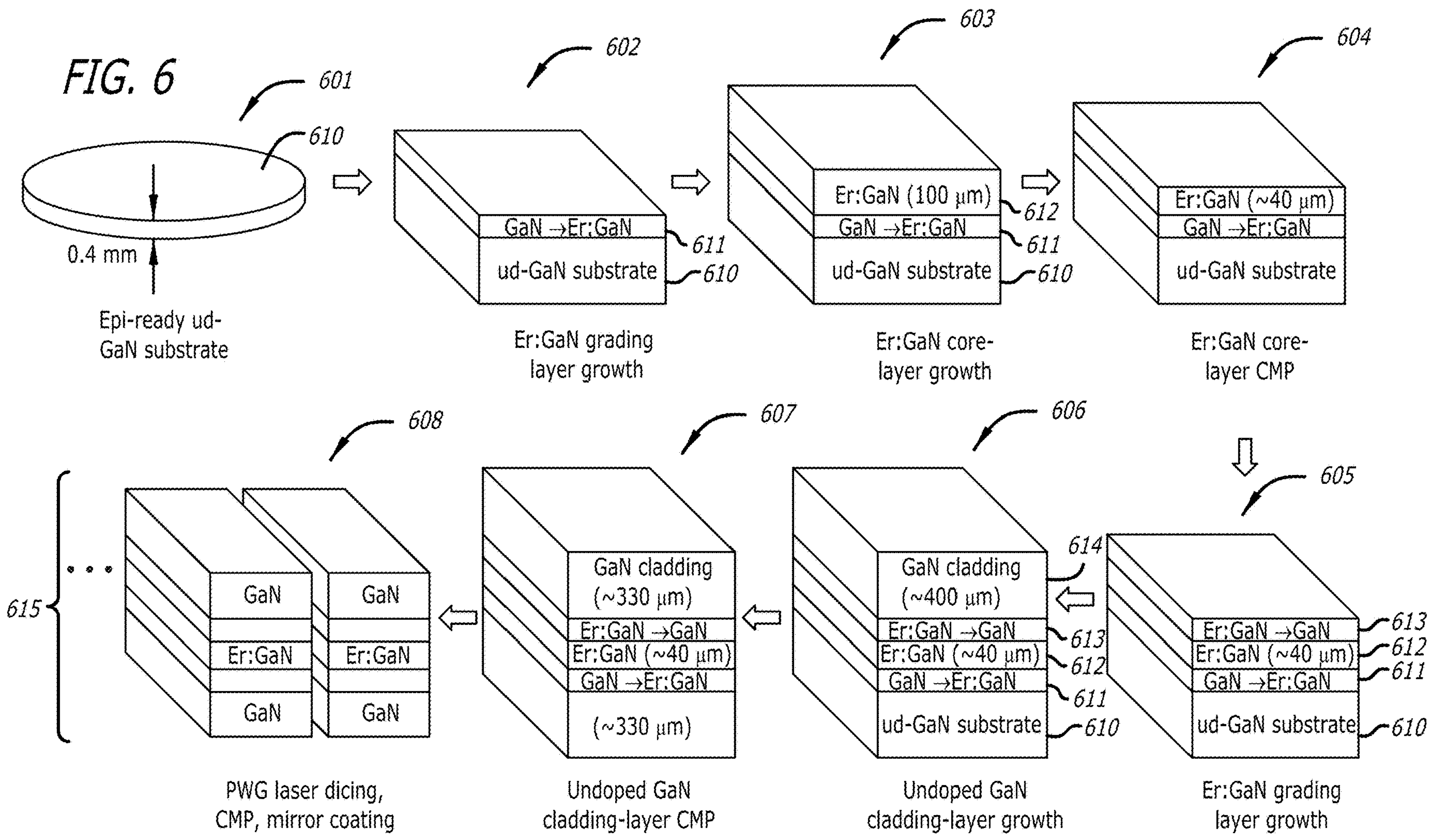


FIG. 6
601
610
0.4 mm
Epi-ready ud-GaN substrate
602
GaN →Er:GaN
ud-GaN substrate
611
610
Er:GaN grading layer growth
603
Er:GaN (100 μm)
GaN →Er:GaN
ud-GaN substrate
612
611
610
Er:GaN core-layer growth
604
Er:GaN (~40 μm)
GaN →Er:GaN
ud-GaN substrate
Er:GaN core-layer CMP
605
Er:GaN →GaN
Er:GaN (~40 μm)
GaN →Er:GaN
ud-GaN substrate
613
612
611
610
Er:GaN grading layer growth
606
GaN cladding (~400 μm)
Er:GaN →GaN
Er:GaN (~40 μm)
GaN →Er:GaN
ud-GaN substrate
614
613
612
611
610
Undoped GaN cladding-layer growth
607
GaN cladding (~330 μm)
Er:GaN →GaN
Er:GaN (~40 μm)
GaN →Er:GaN
(~330 μm)
Undoped GaN cladding-layer CMP
608
GaN
Er:GaN
GaN
GaN
Er:GaN
GaN
PWG laser dicing, CMP, mirror coating
615

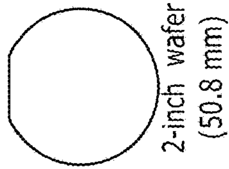


FIG. 7A

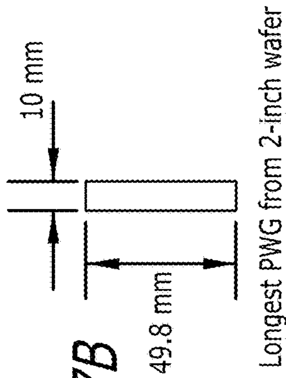


FIG. 7B

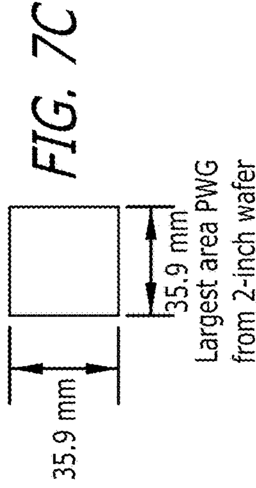


FIG. 7C

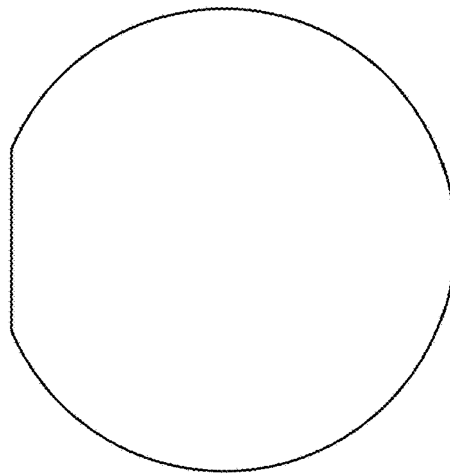


FIG. 7D

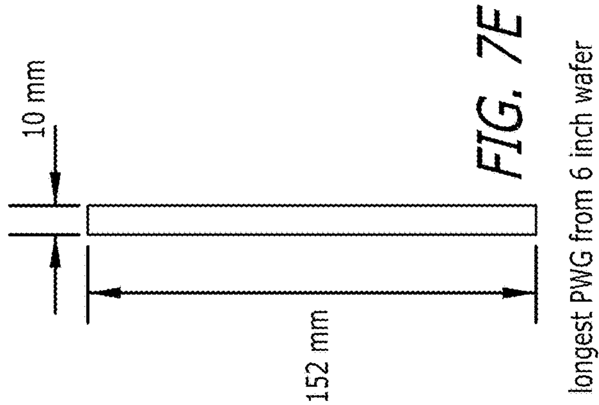


FIG. 7E

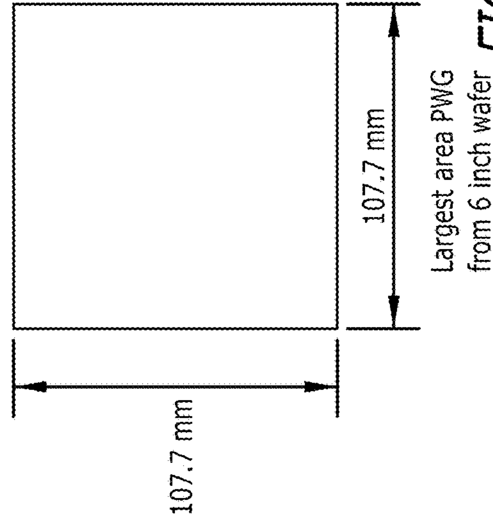


FIG. 7F

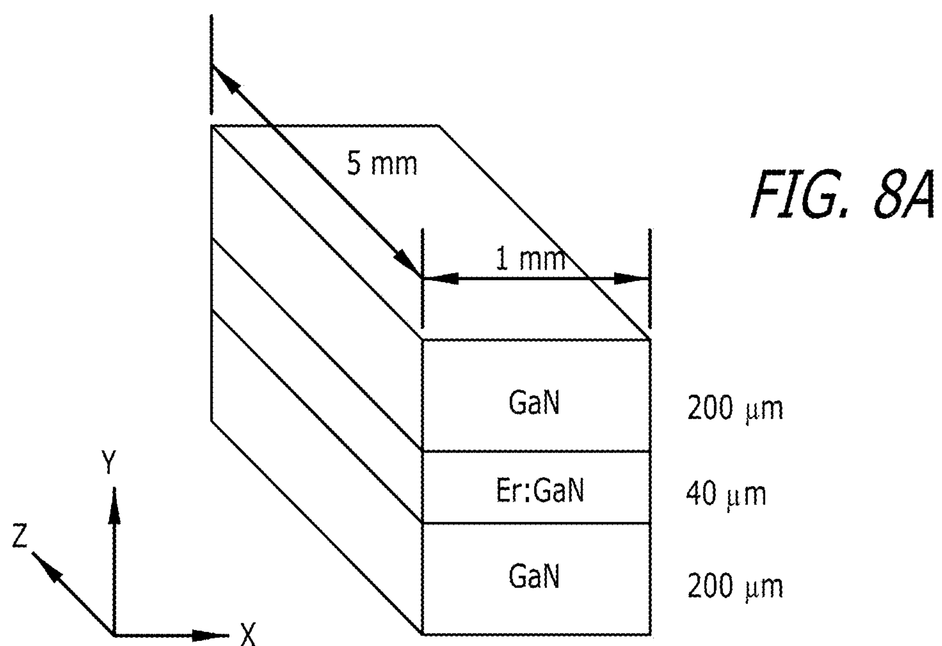


FIG. 8A

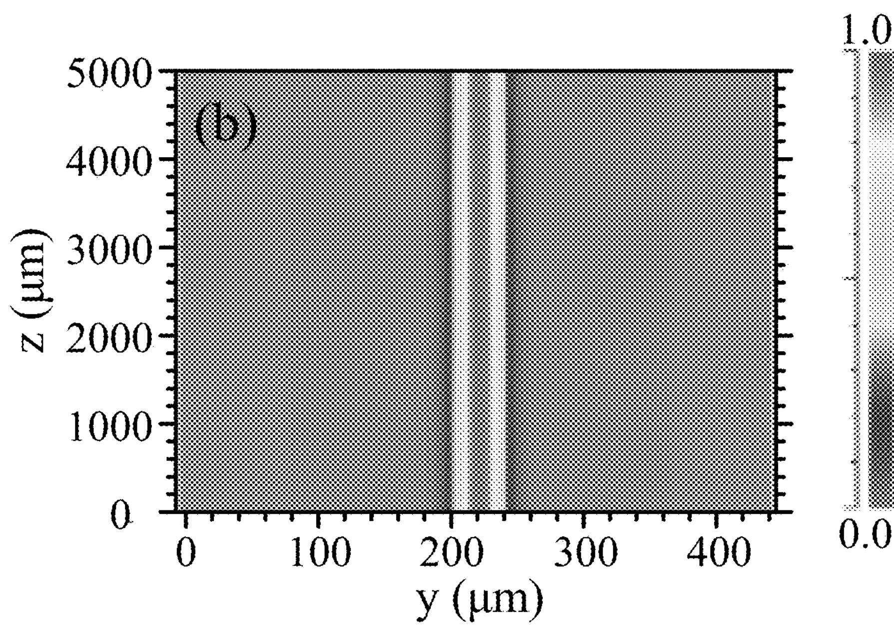
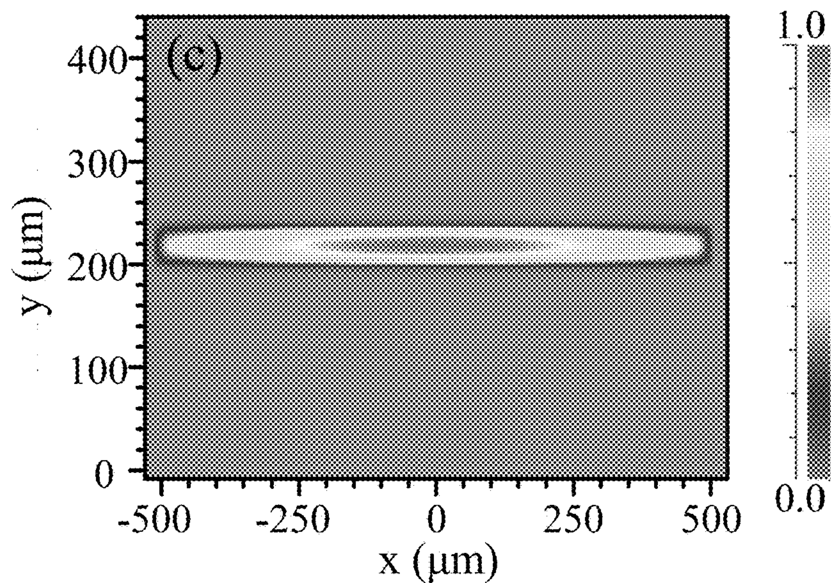


FIG. 8B

FIG. 8C



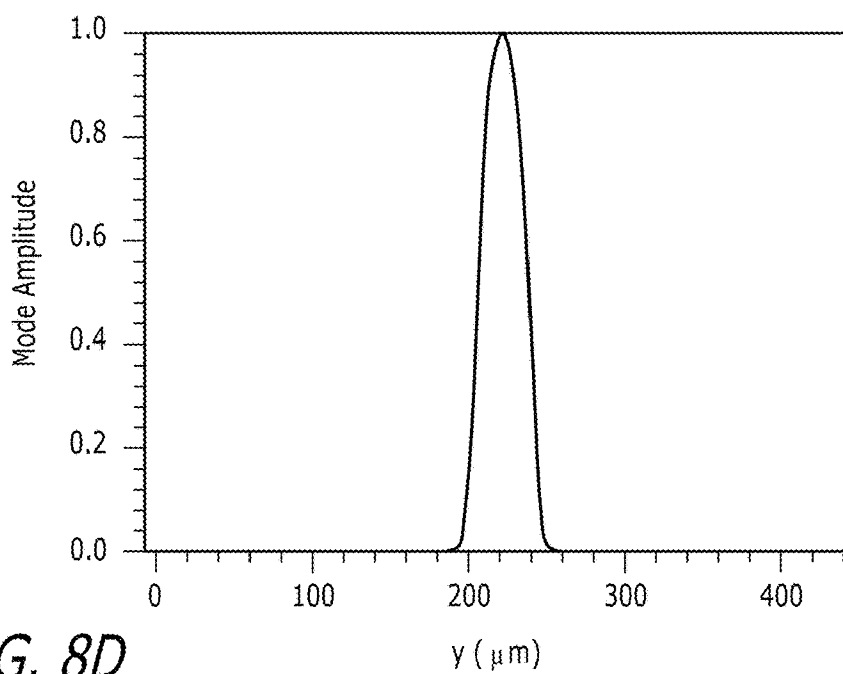


FIG. 8D

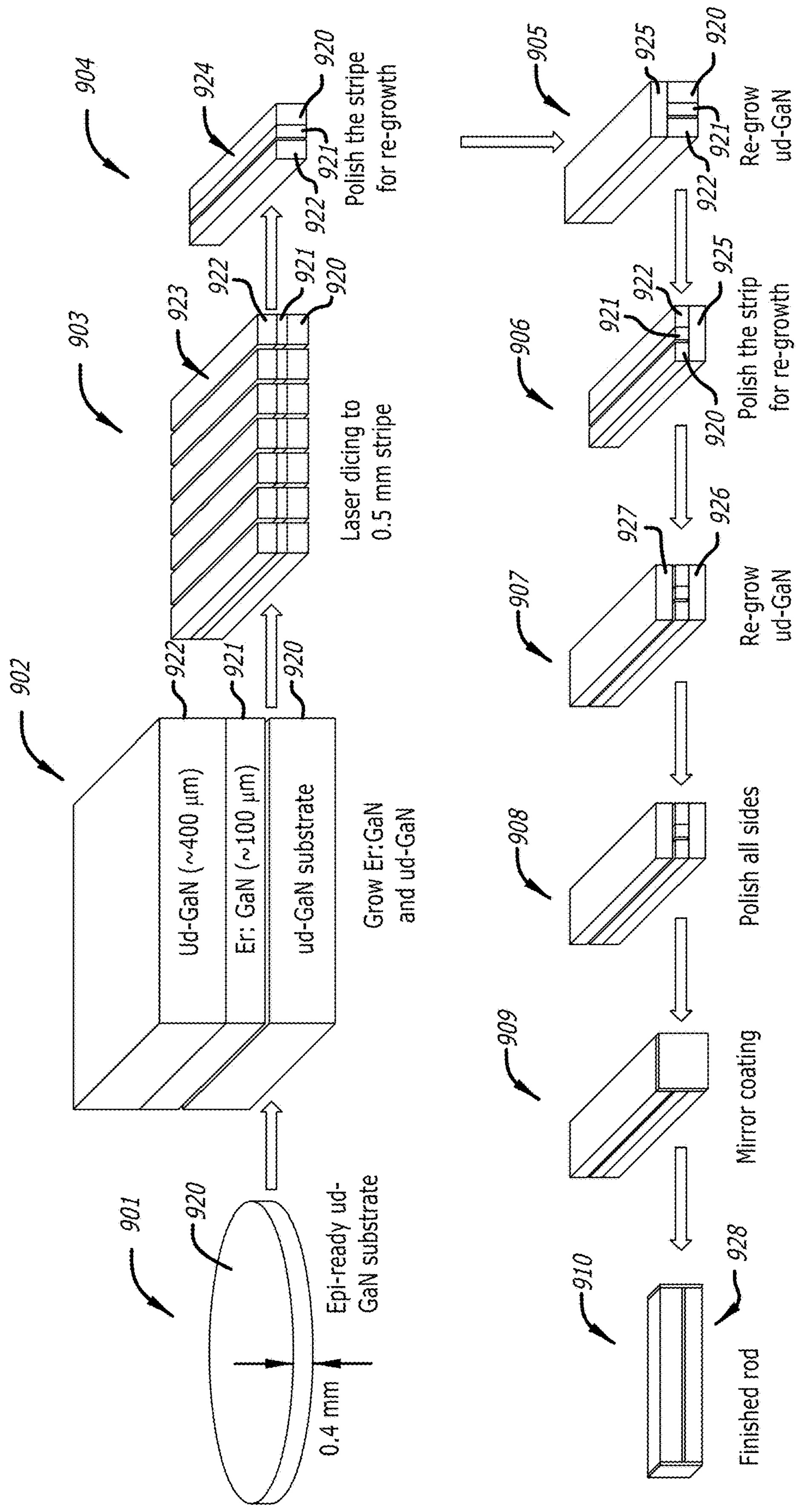


FIG. 9

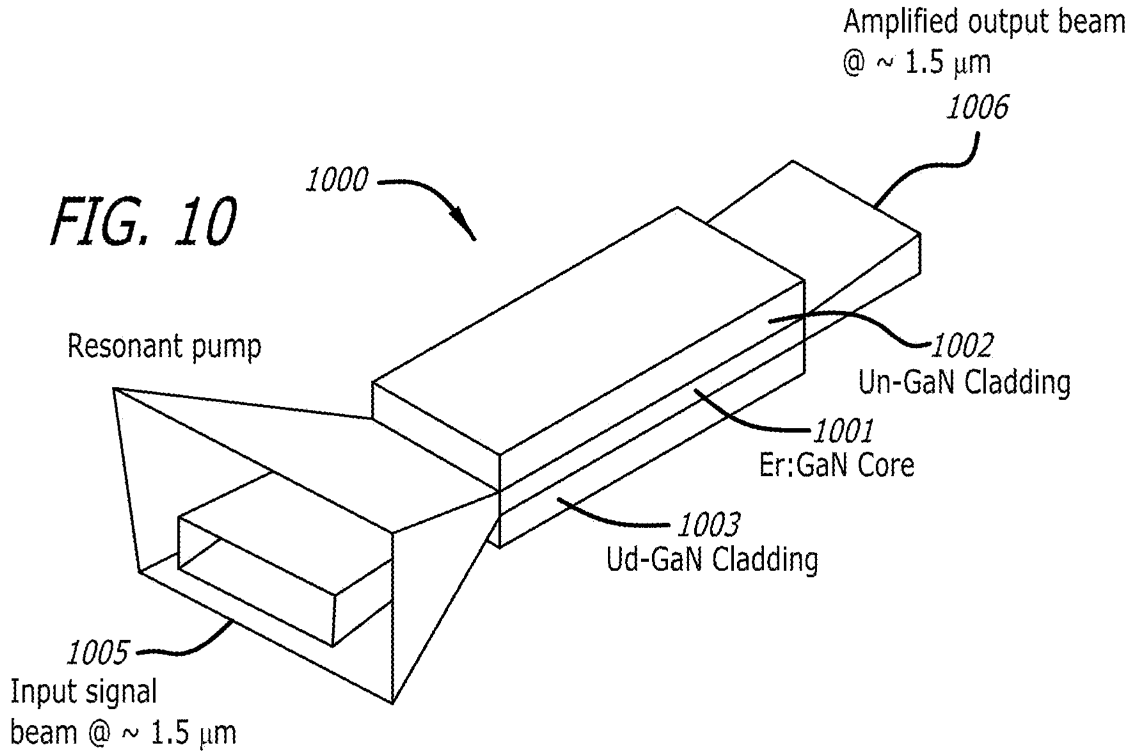


FIG. 10

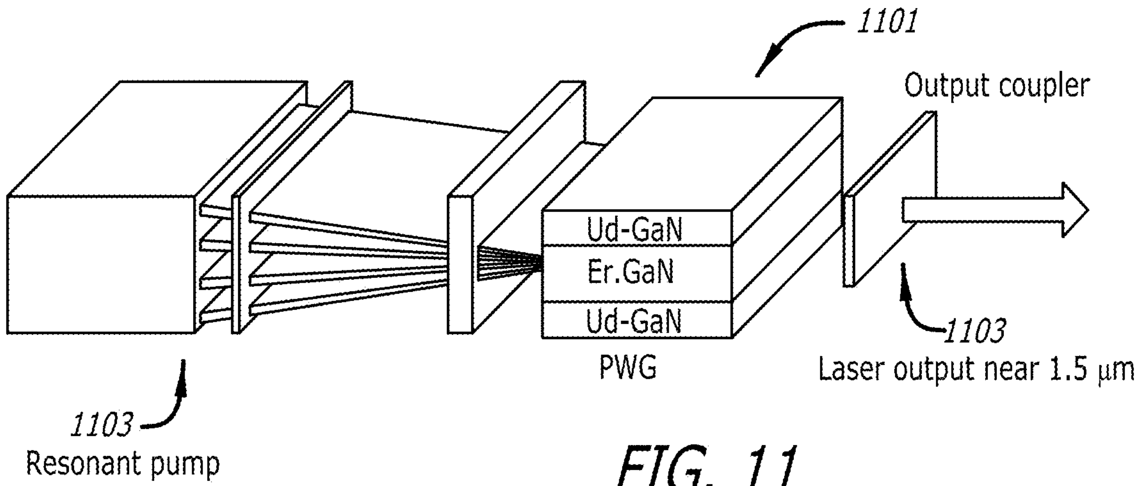


FIG. 11

OPTICAL GAIN MATERIALS FOR HIGH ENERGY LASERS AND LASER ILLUMINATORS AND METHODS OF MAKING AND USING SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Patent Application Ser. No. 62/818,365, filed on Mar. 14, 2019, entitled "NOVEL OPTICAL GAIN MATERIALS FOR HIGH ENERGY LASERS AND LASER ILLUMINATORS", which is hereby incorporated herein by reference in its entirety for all purposes.

STATEMENT REGARDING FEDERALLY FUNDED RESEARCH

[0002] This invention was made with government support under grant/contract number N00014-17-1-2531 awarded by the Directed Energy—Joint Transition Office (JTO) through Office of Naval Research (ONR). The government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] The present invention relates to solid-state and retina-safe high energy lasers and laser illuminators (HELs) based on erbium doped GaN (Er:GaN) quasi-bulk crystals and a method of fabricating gain medium for HELs in the geometries of single crystal core-cladding planar waveguides (PWGs) and optical fibers with the capabilities to outperform HELs based on traditional gain medium such as neodymium doped synthetic crystal of yttrium aluminum garnet (Nd:YAG) in terms of maximum operating power, power density, beam quality, eye safety, and atmospheric transmittance.

BACKGROUND

[0004] Solid-state high energy lasers (HELs) and laser illuminators have been a subject of great interest and under intense development for applications in defense, industrial processing, communications, medicine, spectroscopy, imaging and various other applications [Kalisky 2010; Huber 2010; Koechner 1999; Vetovec 2002; Giesen 2007]. The optical gain medium is the heart of a HEL system. Presently, neodymium doped synthetic crystal of yttrium aluminum garnet (Nd:YAG) emitting at 1.06 μm is one of the most dominant gain medium materials for HELs due partly to the highly developed crystal growth technologies of Nd:YAG. On the other hand, HELs operating at 1.5 μm wavelength region are highly sought-after for applications especially where the laser is expected to travel long distances in free space. Not only the 1.5 μm wavelength window matches with the technologically important wavelength of the minimum propagation loss in optical fibers for telecommunications, but it is also more "retina-safe" as this wavelength is absorbed by the surface of the eye instead of being focused inside at the retina [Boettner 1962], resulting in more than 4 orders of magnitude increase in the upper limit of eye-safe laser exposure power at 1.5 μm over that of the wavelength close to 1 μm or shorter [Zuclich 2007]. Moreover, 1.5 μm lasers also have a higher atmospheric transmittance than that of 1.06 μm lasers [Bailey 2007]. Other applications such as laser radar, rangefinders, target illuminators, IR countermeasures, free space communications, war games devices, and laser weapons can also benefit from the development of improved eye-safer laser sources.

[0005] When doped in a host, the emission lines resulting from the intra-4f transitions from the first excited state manifold ($^4I_{13/2}$) to the ground state manifold ($^4I_{15/2}$) in erbium ions (Er^{3+}) are near 1.5 μm [Desurvire 1994; Mears 1987; Becker 1999; Connelly 2002]. Great progress has been made in the development of HEL gain materials based on Er doped YAG (Er:YAG) [Fan '046 Patent; Ter-Gabrielyan 2013; Spariosu 2006]. However, with the relatively poor thermal properties of YAG having a thermal conductivity of $\kappa \approx 14$ W/m·K and thermal expansion coefficient of $\alpha \approx 8 \times 10^{-6°}$ C.$^{-1}$, the heat dissipation capability of YAG gain medium is relatively poor, which limits the optical output energy and average power. It is presently recognized that damage to the optical gain medium caused by the laser beam flux itself is a principal limitation on further improvement of lasing efficiency [Kalisky 2010; Huber 2010; Koechner 1999; Vetovec 2002; Giesen 2007]. Therefore, the development of new gain materials and structures with improved heat dissipation capability is highly desirable.

SUMMARY OF INVENTION

[0006] The present invention is directed to core-cladding planar waveguide (PWG) structures and methods of making and using same. The core-cladding PWG structures can be synthesized by hydride vapor phase epitaxy and processed by mechanical and chemical-mechanical polishing.

[0007] In general, in one aspect, the invention features a core-cladding planar waveguide (PWG) structure that includes a core layer comprising Er:GaN. The core layer has a uniform Er doping concentration. The core-cladding PWG structure further includes a first GaN layer including undoped GaN. The core-cladding PWG structure further includes a second GaN layer including undoped GaN. The core layer is between the first GaN layer and the second GaN layer.

[0008] Implementations of the invention can include one or more of the following features:

[0009] A first side of the core layer can be adjacent a first side of the first GaN layer. A second side of the core layer can be adjacent a first side of the second GaN layer.

[0010] The core-cladding PWG structure can further include a first transition layer that is between a first side of the first GaN layer and a first side of the core layer. A first side of the first transition layer can be adjacent the first side of the first GaN layer. A second side of the first transition layer can be adjacent the first side of the core layer. Er doping of the first transition layer can be increasing in concentration from the first side of the first transition layer to the second side of the first transition layer. The core-cladding PWG structure can further include a second transition layer that is between a first side of the second GaN layer and a second side of the core layer. A first side of the second transition layer can be adjacent the second side of the core layer. A second side of the second transition layer can be adjacent the first side of the second GaN layer. Er doping of the second transition layer can be decreasing in concentration from the first side of the second transition layer to the second side of the second transition layer.

[0011] The Er doping of the first transition layer can be increasing from a concentration of 0 at the first side of the first transition layer to the Er doping concentration of the core layer at the second side of the first transition layer. The

Er doping of the second transition layer can be decreasing from the Er doping concentration of the core layer at the first side of the second transition layer to a concentration of 0 at the second side of the second transition layer.

[0012] The uniform Er doping of the core layer can be a concentration of at least 1×10^{18} atoms/cm^3.

[0013] The uniform Er doping of the core layer can have a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

[0014] The uniform Er doping of the core layer can be a concentration of at least 1×10^{19} atoms/cm^3.

[0015] The uniform Er doping of the core layer can have a concentration between 1×10^{19} atoms/cm^3 and 1×10^{21} atoms/cm^3.

[0016] The core-cladding PWG structure can have a GaN/Er:GaN/GaN core-cladding PWG structure.

[0017] The core layer can be co-doped with Er and Yb.

[0018] The Er and Yb doping of the core layer can have a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

[0019] The Er and Yb doping of the core layer can have a concentration between 1×10^{19} atoms/cm^3 and 1×10^{21} atoms/cm^3.

[0020] The core layer can have a thickness between of at least 5 μm.

[0021] The core layer can have a thickness between of 5 μm and 200 μm.

[0022] The first GaN layer can have a thickness between 330 μm and 400 μm. The second GaN layer can have a thickness between 330 μm and 400 μm.

[0023] The core-cladding PWG structure can be a strip having a longitudinal axis.

[0024] The core-cladding PWG structure can have a waveguide width that is at most ⅕ the length of the strip along the longitudinal axis.

[0025] In general, in another aspect, the invention features a core-cladding planar waveguide (PWG) structure that includes a core strip including Er:GaN. The core strip has a longitudinal axis. The core strip has a uniform Er doping concentration. The core-cladding PWG structure further includes a GaN layer of undoped GaN that surrounds the core strip along the longitudinal axis.

[0026] Implementations of the invention can include one or more of the following features:

[0027] The GaN layer can be adjacent the core strip along the longitudinal axis.

[0028] The core-cladding PWG structure can further include a transition layer that is between the GaN layer and the core strip. A first side of the transition layer can be adjacent the GaN layer along the longitudinal axis. A second side of the transition layer can be adjacent the core strip. Er doping of the transition layer can be increasing in concentration between the first side of the transition layer to the second side of the transition layer.

[0029] The core-cladding PWG structure of claim **16**, wherein the Er doping of the transition layer can be increasing from a concentration of 0 at the first side of the transition layer to the Er doping concentration of the core stripe at the second side of the transition layer.

[0030] The uniform Er doping of the core strip can have a concentration of at least 1×10^{18} atoms/cm^3.

[0031] The uniform Er doping of the core strip can have a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

[0032] The uniform Er doping of the core strip can have a concentration of at least 1×10^{19} atoms/cm^3.

[0033] The uniform Er doping of the core strip can have a concentration between 1×10^{19} atoms/cm^3 and 1×10^{21} atoms/cm^3.

[0034] The core core-cladding PWG structure can be a GaN/Er:GaN/GaN core-cladding PWG structure.

[0035] The core strip can be uniformly co-doped with Er and Yb.

[0036] The Er and Yb doping of the core strip can have a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

[0037] The Er and Yb doping of the core strip can have a concentration between 1×10^{19} atoms/cm^3 and 1×10^{21} atoms/cm^3.

[0038] In general, in another aspect, the invention features a method of forming a core-cladding planar waveguide (PWG) structure. The method includes the step of selecting an undoped GaN substrate. The method further includes the step of growing a first transition layer on a first side of the undoped GaN substrate. The first transition layer has a first side and a second side. The first side of the undoped GaN substrate is adjacent the first side of the first transition layer. Er doping of the first transition layer is increase in concentration from the first side of the first transition layer to the second side of the first transition layer. The method further includes the step of growing a core layer including Er:GaN on the second side of the first transition layer. The core layer has a first side and a second side. The second side of the first transition layer is adjacent to the first side of the core layer. The core layer has a uniform Er doping concentration. The method further includes the step of growing a second transition layer on the second side of the core layer. The second transition layer has a first side and a second side. The second side of the core layer is adjacent the first side of the second transition layer. Er doping of the first transition layer is decreased in concentration from the first side of the second transition layer to the second side of the second transition layer. The method further includes the step of growing an undoped GaN layer on the second side of the second transition layer to form a core-cladding structure.

[0039] Implementations of the invention can include one or more of the following features:

[0040] The method can further include dicing the core-cladding structure to a pre-determined waveguide width to obtain the core-cladding PWG structure.

[0041] The method can further include lapping and polishing the core-cladding PWG structure.

[0042] The polishing can include mechanical and/or chemical-mechanical polishing.

[0043] The core-cladding PWG structure can have a longitudinal axis.

[0044] The pre-determined waveguide width can be at most ⅕ the length of the core-cladding PWG structure along the longitudinal axis.

[0045] The step of growing the first transition layer can include a first hydride vapor phase epitaxy (HVPE) growth process. The step of growing the core layer can include a second HVPE growth process. The step of growing the second transition layer c can include a third HVPE growth process. The step of growing the undoped GaN layer can include a fourth HVPE growth process.

[0046] The method can be performed utilizing one or more HVPE reactors.

[0047] Each of the steps of growing the first transition layer, growing the core layer, growing the second transition layer, and growing the undoped GaN layer can include utilizing at least one of the one or more HVPE reactors.

[0048] The method can further include the step of, after the step of growing of the core layer utilizing one of the one or more HVPE reactors to form the intermediate structure comprising the undoped GaN substrate, the first transition layer, and the core layer, removing the intermediate structure from the one or more HVPE reactors. The method can further include the step of lapping and polishing the intermediate structure to attain a pre-determined thickness of the core layer. The method can further include the step of, after the step of lapping and polishing the intermediate structure, placing the intermediate structure into the one or more HVPE reactors for performing the step of the step of growing the second transition layer.

[0049] The polishing can include mechanical and/or chemical-mechanical polishing.

[0050] The Er doping of the first transition layer can be increased from a concentration of 0 at the first side of the first transition layer to the Er doping concentration of the core layer at the second side of the first transition layer. The Er doping of the second transition layer can be decreased from the Er doping concentration of the core layer at the first side of the second transition layer to a concentration of 0 at the second side of the second transition layer.

[0051] The uniform Er doping of the core layer can have a concentration of at least 1×10^{18} atoms/cm^3.

[0052] The uniform Er doping of the core layer can have a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

[0053] The uniform Er doping of the core layer can have a concentration of at least 1×10^{19} atoms/cm^3.

[0054] The uniform Er doping of the core layer can have a concentration between 1×10^{19} atoms/cm^3 and 1×10^{21} atoms/cm^3.

[0055] The core-cladding PWG structure can be a GaN/Er:GaN/GaN core-cladding PWG structure.

[0056] The core layer can be uniformly co-doped with Er and Yb.

[0057] The Er and Yb doping of the core layer can have a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

[0058] The Er and Yb doping of the core layer can have a concentration between 1×10^{19} atoms/cm^3 and 1×10^{21} atoms/cm^3.

[0059] The core layer can have a thickness of at least 5 μm.

[0060] The core layer can have a thickness between 5 μm and 200 μm.

[0061] The undoped GaN substrate can have a thickness between 330 μm and 400 μm. The undoped GaN layer can have a thickness between 330 μm and 400 μm.

[0062] In general, in another aspect, the invention features . . .

48. A method of forming one or more core-cladding planar waveguide (PWG) structures. The method includes the step of selecting an undoped GaN substrate having a first side. The method further includes the step of growing a core layer comprising Er:GaN. The core layer has a first side and a second side. The first side of the core layer is facing the first side of the undoped GaN substrate. The core layer has a uniform Er doping concentration. The method further includes the step of growing a first undoped GaN layer to form a first intermediate structure. The first undoped GaN layer has a first side. The first side of the first undoped GaN layer is facing the second side of the core layer. The method further includes the step of dicing the first intermediate structure into a plurality of strips. The strips in the plurality of strips each has a first side, a second side, a third side, and a four side running a longitudinal axis. The first side is undoped GaN. The second side is a first diced surface. The third side is undoped GaN. The fourth side is the second diced surface. The method further includes the step of processing one or more strips in the plurality of strips by the further steps of (i) lapping and polishing the strip, (ii) growing a second undoped GaN layer facing the second side of the strip, and (iii) growing a third undoped GaN layer facing the fourth side of the strip to form a core-cladding planar waveguide (PWG) structure having undoped GaN surrounding the core layer in the strip along the longitudinal axis.

[0063] Implementations of the invention can include one or more of the following features:

[0064] The step of growing the core layer can include growing the core layer on the first side of the undoped GaN substrate. The step of growing the first undoped GaN layer can include growing the first undoped GaN layer on the second side of the core layer.

[0065] The step of growing the second undoped GaN layer can include growing the second undoped GaN layer on the second side of the strip. The step of growing the third undoped GaN layer can include growing the third undoped GaN layer on the fourth side of the strip.

[0066] Before the step of growing a core layer, the method can further include growing a first transition layer on the first side of the undoped GaN substrate. The first transition layer can have a first side and a second side. The first side of the undoped GaN substrate can be adjacent the first side of the first transition layer. Er doping of the first transition layer can be increased in concentration from the first side of the first transition layer to the second side of the first transition layer. The step of growing the core layer can include growing the core layer on the second side of the first transition layer such that the first side of the core layer is adjacent the second side of the first transition layer. Before the step of growing the first undoped GaN layer, the method can further include growing a second transition layer on the second side of core layer. The second transition layer can have a first side and a second side. The second side of the core layer can be adjacent the first side of the second transition layer. Er doping of the second transition layer can be decreased in concentration from the first side of the second transition layer to the second side of the second transition layer. The step of growing the first undoped GaN layer can include growing the first undoped GaN layer on the second side of the second transition layer such that the first side of the GaN layer is adjacent the second side of the second transition layer.

[0067] Before the step of growing the second undoped GaN layer, the method can further include growing a third transition layer on the second side of the strip. The third transition layer can have a first side and a second side. The first side of the third transition layer can be adjacent the second side of the strip. Er doping of the third transition layer can be decreased in concentration from the first side of the third transition layer to the second side of the third transition layer. The step of growing the second undoped

GaN layer can include growing the second undoped GaN layer on the second side of the third transition layer such that the first side of the second undoped GaN layer is adjacent the second side of the third transition layer. Before the step of growing the third undoped GaN layer, the method can further include growing a fourth transition layer on the fourth side of the strip. The fourth transition layer can have a first side and a second side. The first side of the fourth transition layer can be adjacent the fourth side of the strip. The Er doping of the fourth transition layer can be decreased in concentration from the first side of the fourth transition layer to the second side of the fourth transition layer. The step of growing the third undoped GaN layer can include growing the third undoped GaN layer on the second side of the fourth transition layer such that the first side of the third undoped GaN layer is adjacent the second side of the fourth transition layer.

[0068] The uniform Er doping of the core layer can have a concentration of at least 1×10^{18} atoms/cm^3.

[0069] The uniform Er doping of the core layer can have a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

[0070] The uniform Er doping of the core layer can have a concentration of at least 1×10^{19} atoms/cm^3.

[0071] The uniform Er doping of the core layer can have a concentration between 1×10^{19} atoms/cm^3 and 1×10^{21} atoms/cm^3.

[0072] The core-cladding PWG structure can be a GaN/Er:GaN/GaN core-cladding PWG structure.

[0073] The core layer can be uniformly co-doped with Er and Yb.

[0074] The Er and Yb doping of the core layer can have a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

[0075] The Er and Yb doping of the core layer can have a concentration between 1×10^{19} atoms/cm^3 and 1×10^{21} atoms/cm^3.

[0076] The core layer can have a thickness between of at least 5 μm.

[0077] The core layer can have a thickness between of 5 μm and 200 μm.

[0078] The undoped GaN substrate can have a thickness between 330 μm and 400 μm. The first undoped GaN layer can have a thickness between 330 μm and 400 μm. The second undoped GaN layer can have a thickness between 330 μm and 400 μm. The third undoped GaN layer can have a thickness between 330 μm and 400 μm.

[0079] In general, in another aspect, the invention features a core-cladding planar waveguide (PWG) structure that includes a core layer including Er:GaN. The core layer has a uniform Er doping concentration. The core-cladding PWG structure further includes a first layer comprising $Al_xGa_{1-x}N$ and a second layer comprising $Al_xGa_{1-x}N$, with x being between 0 and 1, inclusive. The core layer is between the first layer and the second layer.

[0080] Implementations of the invention can include one or more of the following features:

[0081] The core-cladding PWG structure can further include a first transition layer between the first layer and the core layer. The first transition layer can have an Er doping concentration that increases between (i) a first surface of the first transition layer adjacent to the first layer, and (ii) a second surface of the first transition layer adjacent the core layer. The core-cladding PWG structure can further include a second transition layer between the core layer and the second layer. The second transition layer can have an Er doping concentration that decreases between (i) a first surface of the second transition layer adjacent to the core layer, and (ii) a second surface of the second transition layer adjacent the second layer.

[0082] In general, in another aspect, the invention features a core-cladding planar waveguide (PWG) structure that includes a core strip including Er:GaN. The core strip has a longitudinal axis. The core strip has a uniform Er doping concentration. The core-cladding PWG structure further includes a first layer of $Al_xGa_{1-x}N$ that surrounds the core strip along the longitudinal axis, with x being between 0 and 1, inclusive.

[0083] Implementations of the invention can include one or more of the following features:

[0084] The core-cladding PWG structure can further include a transition layer between the core strip and the first layer. The transition layer can have an Er doping concentration that increases between (i) a first surface of the first transition layer adjacent to the first layer, and (ii) a second surface of the transition layer adjacent the core strip.

[0085] In General, in Another Aspect, the Invention Features

[0086] A device comprising any of the above core-cladding planar waveguide (PWG) structures. The core-cladding PWG structure is a gain medium in the device.

[0087] Implementations of the invention can include one or more of the following features:

[0088] The device can be selected from a group consisting of optical amplifiers, laser illuminators, and high-energy lasers.

[0089] The device can be operable to operate in a retina safe window.

[0090] The device can further include a resonant pump.

[0091] The core-cladding PWG structure can have a core region operable to have an optical confinement of at least 96%.

[0092] The core-cladding PWG structure can have a core region operable to have an optical confinement between 96% and 99%.

[0093] The core-cladding PWG structure can have a core region operable to have an optical confinement of at least 99%.

BRIEF DESCRIPTION OF DRAWINGS

[0094] FIG. **1**A is a flow chart for obtaining freestanding Er doped GaN (Er:GaN) quasi-bulk crystals.

[0095] FIG. **1**B are optical images of a freestanding Er:GaN wafer of 1 mm in thickness.

[0096] FIG. **2**A is a graph of XRD θ-2θ scans of the GaN (0002) diffraction peak of a freestanding Er:GaN sample before polishing (1.2 mm in thickness) and after double-side polishing (1 mm in thickness).

[0097] FIG. **2**B is a graph of Er concentration profile in a 1 mm thick freestanding Er:GaN quasi-bulk crystal probed by secondary mass spectrometry (SIMS) up to 3 μm in depth from a polished surface.

[0098] FIG. **3**A is a graph showing the comparison of room temperature PL spectra of freestanding Er:GaN samples of two different thicknesses of 1 mm and 11 μm excited by band-edge excitation at λ_{exc}=375 nm.

[0099] FIG. **3**B is a graph showing is the comparison of room temperature PL spectra of freestanding Er:GaN

samples of two different thicknesses of 1 mm and 11 μm excited by resonant excitation at λ_{exc}=980 nm.

[0100] FIG. **3**C is a graph showing the 1.54 μm emission decay kinetics in Er:GaN excited by a 375 nm laser diode measured at room temperature.

[0101] FIG. **3**D is a graph showing the 1.54 μm emission intensity of a 1 mm thick freestanding Er:GaN sample as a function of temperature.

[0102] FIGS. **4**A-**4**B are optical images of various laser structures (rods in FIG. **4**A and disks in FIG. **4**B) fabricated from 2-inch diameter Er:GaN quasi-bulk crystals via HVPE growth, laser cutting and chemical and mechanical polishing (CMP).

[0103] FIG. **5** is a flow chart for synthesizing and processing GaN/Er:GaN/GaN core-cladding planar waveguide (PWG) optical gain medium structures by HVPE growth, laser dicing, and chemical and mechanical polishing (CMP).

[0104] FIG. **6**. is another flow chart for synthesizing and processing GaN/Er:GaN/GaN core-cladding planar waveguide (PWG) optical gain medium structures by HVPE growth, laser dicing, and chemical and mechanical polishing (CMP), and HYPE re-growth.

[0105] FIGS. **7**A-**7**C are illustrations of the longest length and largest area of PWGs that can be fabricated from Er:GaN quasi-bulk crystals of 2-inches in diameter.

[0106] FIGS. **7**D-**7**F are illustrations of the longest length and largest area of PWGs that can be fabricated from Er:GaN quasi-bulk crystals of 6-inches in diameter.

[0107] FIGS. **8**A-**8**D depict optical intensity distribution of a representative GaN/Er:GaN/GaN core-cladding PWG. FIG. **8**A is a schematic of a GaN/Er:GaN/GaN core-cladding PWG consisting of a 40 μm Er:GaN core and 200 μm GaN claddings. The waveguide structure has a width (along x-axis) of 1 mm and a length (along z-axis) of 5 mm and an Er doping concentration in the core of $3\times10^{'9}$ atoms/cm^3. FIG. **8**B is an optical intensity distribution across the Er:GaN core region and along the propagation direction, z-axis. FIG. **8**C is a transverse electric (TE) mode profile of the x-y cross-section plane. FIG. **8**D is a mode amplitude profile along y-axis.

[0108] FIG. **9** is a flow chart for synthesizing and processing GaN/Er:GaN/GaN core-cladding fiber gain medium structures by HVPE growth, laser dicing, chemical and mechanical polishing (CMP) and HVPE re-growth.

[0109] FIG. **10** is a schematic of employing GaN/Er:GaN/GaN core-cladding PWG/core-cladding fiber structure as a gain medium in an optical amplifier/laser illuminator.

[0110] FIG. **11** is a schematic of employing GaN/Er:GaN/GaN core-cladding PWG structure as a gain medium in a high energy laser.

DETAILED DESCRIPTION

[0111] III-nitride wide bandgap semiconductor materials (i.e., GaN and its family members of InN, InGaN, AlN, AlGaN, and their alloy combinations), which have demonstrated excellent performances in high power, high temperature electronics and optoelectronics [Bergh 2001; Narukawa 2007; Day 2011; Nakamura 2000], are very promising as a gain medium material for HELs. It was established that in erbium (Er) doped III-nitrides (Er:InGaN, Er:GaN and Er:AlN, Er:AlGaN, and Er:InAlGaN) the emission resulting from the intra-4f transition from the first excited manifold ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) in Er^{3+} ions is around 1.5 μm [Favennec 1989]. To the first order, the maximum achievable lasing power (P_{max}) for a solid-state laser gain medium attached to a heat sink is characterized roughly by the thermal shock parameter, $P_{max}\sim\kappa/\alpha^2$, where κ is the thermal conductivity and α is the thermal expansion coefficient of the gain material. TABLE I presents a comparison between important material parameters for using Nd:YAG or Er:GaN as an optical gain medium for high energy lasers. GaN has a much larger thermal conductivity (κ=253 W/m·K) [Shibata 2007] and lower thermal expansion coefficient ($\alpha\approx3.53\times10^{-6\circ}$ C.$^{-1}$) [Shibata 2007] than YAG (κ=14 W/m·K, $\alpha\approx8\times10^{-6\circ}$ C.$^{-1}$).

TABLE 1

Comparison of important material parameters between Nd:YAG and Er:GaN as optical gain medium for high energy lasers

Laser gain material	Nd:YAG	Er:GaN bulk crystals
Crystal structure	Cubic	Wurtzite
Lattice constant (Å)	12.01	α = 3.186, c = 5.186
Moh Hardness	8.5	9
Emission wavelength, λ_{emi} (μm)	~1.06	~1.54
Thermal conductivity, κ (W/m · K) @ 300K	14	253
Density (g/cm^3)	4.56	6.15
Melting temperature (° C.)	1970	>2500
Radiative lifetime (ms)	0.95	2.8
Thermal expansion coefficient (× 10^{-6} ° C.$^{-1}$)	8	3.53
Index of Refraction, n @ λ_{emi}	1.82	2.34

[0112] Thus, the theoretical maximum lasing power of HELs based on Er:GaN can surpass that of those based on Nd:YAG by a factor up to 90. Moreover, with GaN possessing a small variation of the refractive index (n) with temperature (T), dn/dT=$0.7\times10^{-5\circ}$ C.$^{-1}$ at 1.5 μm [Hui 2005], GaN host potentially provides an excellent beam quality. Furthermore, due to its wide energy bandgap nature, it was shown that the 1.5 μm emission in Er:GaN has an excellent thermal stability [Favennec 1989; Ugolini 2006]. Therefore, with superior thermal and mechanical properties, HELs based on Er:GaN are potentially capable of outperforming YAG HELs in terms of maximum operating power, power density and beam quality as well as eye-safety and atmospheric transmittance.

[0113] Although Er:GaN is known to have a great potential to offer many advantages as a HEL gain medium over more traditional optical gain materials such as Nd:YAG, most of the previous works were limited to Er doped III-nitride epitaxial layers of only a few microns in thickness produced by epitaxial growth techniques such as metal organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE) with a focus on applications of Er:GaN for light emitting diodes, full color displays, and chip scale amplifiers for optical communications [Ugolini 2006; Wilson 1994; Garter 1999; Zavada 2004; Steckl 2002; Dahal 2010; Jiang '328 Patent; Dahal 2009]. The material growth technologies for producing Er:GaN quasi-bulk crystals (crystals with a thickness from tens to thousands of microns) which are needed for the construction of active optical gain medium in various geometries for HELs have not been in existence until recently [Jeon 2015; Sun 2016; Sun 2017; Sun 2018].

[0114] The present inventors have recently developed a hydride vapor phase epitaxy (HVPE) growth technique for

the synthesis of Er:GaN quasi-bulk single crystal wafers [Jeon 2015; Sun 2016; Sun 2017; Sun 2018]. HVPE technique is an established technique with abilities to employ high purity precursors to provide GaN quasi-bulk crystal growth with high crystalline quality at a growth rate as high as hundreds of microns per hour [Motokia 2002]. As illustrated in FIGS. **1**A-**1**B, freestanding single crystal Er:GaN wafers with thicknesses on the millimeter scale has been obtained via HVPE growth in conjunction with a laser-lift-off (LLO) process [Sun 2016; Sun 2017; Sun 2018]; the realized Er:GaN bulk materials are single crystals as demonstrated by the x-ray diffraction (XRD) results shown in FIG. **2**A, which shows the X-ray diffraction (XRD) θ-2θ scans of the GaN (0002) diffraction peaks of a freestanding Er:GaN sample before (plot **201**) and after (plot **202**) subjected to a chemical-mechanical polishing (CMP) processing. (Dashed line **203** at 34.570° represents the position of the 2θ diffraction angle of the GaN (0002) peak in strain-free undoped GaN). Comparison of the peak positions at 34.466° and 34.545°, respectively, for the wafer before and after CMP with the 2θ diffraction peak of strain-free GaN (0002) at 34.570°, reveals the presence of a compressive strain in Er:GaN wafer. However, the smoothing of the surface and removal of shallow defects by CMP can reduce the stress in the wafer, as suggested by the observed shift of the 2θ diffraction peak position toward that of the strain-free GaN (0002) after wafer CMP.

[0115] The presence of a slight difference in the peak positions of the 2θ angle between the polished freestanding Er:GaN sample and the strain-free GaN is due to the fact that the size of Er atom is larger than that of the Ga atom and the majority of Er ions in GaN occupy Ga substitutional sites [Mishra 2007; Wahl 2003]. In one example, an Er doping level of 1.4×10^{20} atoms/cm^3 has been confirmed by secondary ion mass spectrometry (SIMS) measurement (FIG. **2**B) [Sun 2016].

[0116] As shown in FIGS. **3**A-**3**B, the freestanding Er:GaN wafers exhibit strong emission at 1.54 μm with their emission intensity increasing dramatically with wafer thickness under 980 nm resonant excitation. In FIGS. **3**A-**3**B, plots **301** and **303** are for freestanding ER:GaN (~1 mm) and plots **302** and **304** are for ER:GaN (HVPE) (~11 μm),

[0117] The results shown in FIGS. **3**A-**3**B can be explained by the fact that the band-edge photons at 375 nm have a large optical excitation cross section (4.6×10^{-17} cm^2) [Feng 2003], translating to a small penetration depth of <2 μm. This means that the 375 nm photons are completely absorbed within the top surface of 2 μm. Therefore, increasing the sample thickness has no effects on the PL emission intensity at 1.54 μM. In contrast, 980 nm photons provide a resonant excitation in Er^{3+} with an excitation cross section of about 2.2×10^{-21} cm^2 [Wang 2011], giving a penetration depth of >1 mm. Therefore, the 1 mm freestanding Er:GaN wafer absorbs much more power of 980 nm excitation laser than the 11 μm thick wafer, resulting in a much higher emission intensity at 1.54 μm.

[0118] As shown in FIG. **3**C, the decay lifetime constant of the 1.54 μm emission is on the millisecond scale. These results establish the basis for achieving carrier inversion between $^4I_{13/2}$ to $^4I_{15/2}$ levels and lasing emission at 1.54 μm. A very low thermal quenching of only 10% for the 1.54 μm emission intensity between 10 K and 300 K has been measured (FIG. **3**D), confirming that 1.54 μm emission in Er:GaN is highly thermally stable at room and elevated temperatures [Sun 2016]. As shown in FIG. **4**A-**4**B, various Er:GaN laser structures, including laser rods (FIG. **4**A) and disks (FIG. **4**B) have been successfully fabricated.

[0119] These results show that it is feasible to produce Er:GaN quasi-bulk crystals with high crystalline quality by HVPE and opened up new prospects of employing Er:GaN as an outstanding gain medium for HELs. However, to enable practical optical amplifier or laser applications, the design geometry of the gain medium material can make a huge difference to the overall laser performance. A need remains in the art of growth, processing and fabrication of Er:GaN optical gain medium in appropriate geometries.

[0120] The present invention pertains to the synthesis of Er doped III-nitride quasi-bulk crystals and the associated optical gain medium structures by HVPE and fabrication of optical gain medium in suitable geometries for HEL and laser illuminators operating at the "retina-safe" wavelength window (near 1.5 μm). A gain medium of HEL or laser illuminator must be fabricated into appropriate geometries, such as disks, rods, slabs, and core cladding planar waveguides (PWG) and core cladding fiber-like structures to provide an effective optical confinement, pumping efficiency, and hence optimal performance. Among different geometries, the core-cladding structures have the advantages of reduced optical loss, enhanced optical gain and reduced lasing threshold as the optical energy is confined in the core layer. In particular, the core-cladding PWG structure possesses a sufficiently large surface area to provide an excellent heat removal capability, thereby minimizing the thermal impact during high power/energy operation. The core-cladding structures are also highly compatible with high-power laser diode clad pumping schemes [Grivas 2011]. Therefore, GaN/Er:GaN/GaN core-cladding structures in various form factors represent a very promising design architecture to realize a new generation gain medium for HELs. This present invention teaches how to realize optical gain medium in the core-cladding PWG and core-cladding fiber-like geometries.

[0121] The principle for realizing core-cladding Er:GaN gain medium structures is based on the fact that the refractive index of Er doped GaN increases almost linearly with an increase in the Er doping concentration [Alajlouri 2014]. This property together with HVPE growth capabilities leads to a very unique and important advantage of Er:GaN gain material synthesized by HVPE, which is that in principle we can synthesize core-cladding structures (such as PWGs) in a single growth run by using Er doped layer as the core and undoped GaN as the gladding layers so that the highly effective clad pumping scheme can be employed.

[0122] One embodiment of the present invention, shown in FIG. **5**, provides a method for fabricating a core-cladding PWG **513** by starting, in step **501**, from an epi-ready undoped GaN bulk substrate **510**. In step **502**, a transition layer **511** with a certain thickness (e.g., ~20 μm) with Er doping level gradually increasing from undoped GaN to Er:GaN is grown. In step **503**, the method is followed by the growth of the Er:GaN layer **512** with a uniform Er doping concentration to serve as the core-layer. The thickness of this core layer can be varied for example from 30 μm to 200 μm depending on application scenarios. After the growth of the Er:GaN core layer **512**, in step **504**, another transition layer **513** with a certain thickness (e.g., ~20 μm) with Er doping level gradually decreasing from Er:GaN to undoped GaN is grown, In step **505**, the method is followed by the growth of

~400 μm thick undoped GaN **514** as the top cladding layer. The insertion of the transition layers **511** and **513** before and after the Er:GaN core layer **512** is to mitigate any disadvantageous effects of stain induced by the slight lattice mismatch between Er:GaN and undoped GaN, as the lattice constant of Er:GaN is slightly larger than GaN because the atomic size of Er is larger than Ga, a case which is suggested by the XRD results shown in FIG. **2**A. After the HVPE growth, in step **506**, the wafer is diced into strips (or waveguides) with a desired waveguide width to obtain GaN/Er:GaN/GaN core-cladding PWGs **515**. Each side of PWG **515** is subject to lapping, mechanical and chemical-mechanical polishing (CMP) to minimize the optical loss.

[0123] Another embodiment of the present invention, shown in FIG. **6**, provides a method for fabricating a core-cladding PWG **615** by starting from, in step **601**, an epi-ready undoped GaN bulk substrate **610**. In step **602**, a transition layer **611** of a certain thickness (e.g., ~20 μm) with Er doping level gradually increasing from undoped GaN to Er:GaN is grown. In step **603**, the method is followed by the growth of the Er:GaN layer **612** with a uniform Er doping concentration to serve as the core-layer. The thickness of this core layer **612** can be as thick as 200 μm. After the growth of the Er:GaN core layer, in step **604**, the Er:GaN/GaN wafer is taken out from the HVPE reactor and processed by lapping, mechanical and chemical-mechanical polishing to attain a desired thickness (e.g., 30 μm thick Er:GaN core layer). The purpose of CMP processing is to improve the surface morphology and make the Er:GaN/GaN wafer truly epi-ready for the subsequent growth of the undoped GaN cladding layer in case the as-grown surface of Er:GaN is not ideal for subsequent growth, as the incorporation of Er during HVPE growth process may cause surface roughness. In step **605**, the epi-ready Er:GaN/GaN wafer is then put back into the HVPE reactor and proceeds with the re-growth on the epi-ready Er:GaN/GaN wafer of another transition layer **613** with a certain thickness (e.g., ~20 μm) with Er doping level gradually decreasing from Er:GaN to undoped GaN. In step **606**, the method is followed by the growth of a ~400 μm thick undoped GaN **614** as the top cladding layer. After the HVPE growth, in step **607**, the wafer is diced into strips (or waveguides) with a desired waveguide width to obtain GaN/Er:GaN/GaN core-cladding PWGs. In step **608**, each side of PWG **615** is subject to lapping, mechanical and chemical-mechanical polishing (CMP) to minimize the optical loss.

[0124] As shown schematically in FIGS. **7**D-**7**F, the longest PWG that can be fabricated from 6-inch wafers is about 15 cm, whereas, as shown schematically in FIGS. **7**A-**7**C, the longest PWG that can be fabricated from 2-inch wafers is about 5 cm. However, a single wafer can be diced into many strips with different widths and different lengths to obtain PWGs of various sizes. The largest square shaped PWG can be fabricated from a 6-inch wafer is 107.7 mm×107.7 mm.

[0125] Due to the refractive index difference between undoped GaN cladding layer and the Er:GaN core layer, a GaN/Er:GaN/GaN PWG provides an excellent optical confinement along the c-axis of GaN, thereby enable an excellent efficiency for the pumping laser that excites the Er^{3+} ions in the core region. FIGS. **8**A-**8**D show the optical intensity distribution in a representative core-cladding PWG consisting of GaN (200 μm)/Er:GaN (40 μm)/GaN (200 μm) layer structure shown in FIG. **8**A with a waveguide width of 1 mm in the horizontal (x–) direction and a length of 5 mm in the propagation (z–) direction. Using an Er doping concentration of $[Er]=3\times10^{19}$ atoms/cm^3 in the Er:GaN core layer, the refractive index difference between the Er:GaN core layer and the GaN cladding layer is 0.00172 [Alajlouri 2014]. FIG. **8**B presents the optical intensity distribution across the Er:GaN (40 μm) core and along the propagation z-direction, without considering propagational losses. FIG. **8**C shows the transverse electric (TE) mode profile of the x-y cross-section at any z position, indicating a good optical confinement. FIG. **8**D shows the corresponding mode amplitude profile along the y-axis (across the Er:GaN core region) at any z position.

[0126] A 94% of optical confinement of the power can be achieved in the 40 μm Er:GaN core region. TABLE II shows that by fixing the top and bottom cladding layer thickness at 200 μm, changing the thickness of the Er:GaN core layer from 5 μm to 200 μm, and the Er doping level in the core layer from 1×10^{19} cm^{-3} to 1×10^{21} cm^{-3}, the corresponding optical confinement factor (%) can be controlled.

TABLE II

Optical confinement in GaN/Er:GaN/GaN core-cladding PWGs (measured in percent)

	N_{Er} ($\times10^{19}$ cm^{-3})												
d(μm)	1	2	3	4	5	6	7	8	9	10	20	50	100
5	10.3	23.8	33.4	40.6	46.4	50.8	54.8	57.9	57.9	60.6	76.2	88.0	93.1
10	28.7	48.3	59.0	65.9	70.7	74.2	77.2	81.0	82.7	84.3	90.8	96.3	98.0
15	43.8	62.8	72.0	77.5	81.1	84.0	85.9	87.9	89.3	90.6	95.9	98.2	99.1
20	58.8	74.7	81.8	85.9	89.0	91.1	92.7	93.9	94.7	95.3	97.5	98.9	99.5
30	70.5	83.5	86.6	93.2	95.2	96.1	96.7	97.1	97.4	97.7	98.8	99.5	99.7
40	77.1	88.9	94.0	96.3	97.2	97.6	98.0	98.2	98.4	98.5	99.3	99.7	99.8
50	81.3	92.0	96.0	97.4	98.0	98.3	98.5	98.7	98.9	99.0	99.5	99.8	99.9
60	84.3	93.6	96.9	98.0	98.4	98.7	98.9	99.0	99.1	99.2	99.6	99.8	99.9
70	86.1	94.4	97.4	98.3	98.7	98.9	99.1	99.2	99.3	99.3	99.7	99.9	99.9
80	87.3	95.0	97.6	98.5	98.9	99.1	99.2	99.3	99.4	99.4	99.7	99.9	99.9
90	88.1	95.3	97.8	98.6	99.0	99.2	99.3	99.4	99.4	99.5	99.7	99.9	99.9
100	88.9	95.5	97.8	98.7	99.1	99.2	99.3	99.4	99.5	99.5	99.8	99.9	100.0
200	92.2	96.4	98.0	98.8	99.3	99.5	99.6	99.7	99.7	99.7	99.9	100.0	100.0

Top and bottom cladding layer thickness = 200 μm

Core thickness = d (μm)

Er concentration in the core = N_{Er} ($\times10^{19}$ cm^{-3})

[0127] For the case with the Er:GaN core layer thickness of 50 μm and a doping concentration of 3×10^{19} atoms/cm^3 and the top and bottom cladding layer thickness of 200 μm, an optical confinement as high as 96% can be obtained in the Er:GaN core region. In another case with the Er:GaN core layer thickness of 50 μm and a doping concentration of 1×10^{20} atoms/cm^3 and the top and bottom cladding layer thickness of 200 μm, an optical confinement as high as 99% can be obtained in the Er:GaN core region.

[0128] One embodiment of the present invention provides a method for fabricating a core-cladding all crystal fibers **928**, as shown in FIG. **9**. These devices are expected to enable lasers and laser illuminators with much more output power than those using conventional glass fibers. In step **901**, the method starts from an epi-ready undoped GaN bulk substrate **920**. In step **902**, a Er:GaN core layer **921** is grown, followed by the growth of ~400 μm thick undoped GaN as a cladding layer **922**. After the HVPE growth, in step **903**, the wafer is diced into strips **922**. In step **904**, each strip **923** is subjected to CMP to obtain smooth surfaces in an epi-ready state (polished strips **924**). In step **905**, the polished strip **924** is then put back into HVPE reactor for the re-growth of ~400 μm thick undoped GaN as a cladding layer **925** on one of the diced surfaces. In step **906**, the method is then followed by another CMP and, in step **907**, another regrowth of undoped GaN cladding layer **926** to complete the formation of a core-cladding fiber structure **927**. In step **908**, the core-cladding fiber structure **927** is subjected to final CMP and, in step **909**, mirror coating to enhance the performance (finished core cladding fiber **928**). The maximum length of a finished core cladding fiber **928** fabricated from a 6-inch diameter wafers is 15 cm. With an appropriate core diameter, which can be varied, and high Er concentration up to -10^{21} cm^{-3}, these structures should be capable of producing high power output under resonant pump using 980 nm laser diodes.

[0129] In another embodiment of the present invention, the core region is co-doped with Er and Yb. Co-doping significantly alters the Er dopant's environment. The absorption cross section of Yb^{3+} at 980 nm is about 7 times larger than that of Er^{3+}, and its absorption band extends over a wider wavelength region, between 850 nm and 1000 nm [Koechner 1999]. The energy is then transferred resonantly from Yb^{3+} to the $^4I_{11/2}$ state of Er^{3+}. Therefore, Yb and Er co-doping scheme can enhance the effective excitation cross section and hence the pumping efficiency at 980 nm by a factor of 7. The Er and Yb doping concentrations can be varied from a few $10^{19}/cm^3$ to $10^{21}/cm^3$ depending on specific applications.

[0130] In another embodiment of the present invention, the cladding layer is $Al_xGa_{1-x}N$ with x varying from 0 to 1. Since the refractive index of $Al_xGa_{1-x}N$ monotonically decreases with an increase of the Al molar fraction [Hui 2005], compared to the use of undoped GaN as cladding layers, the use of undoped $Al_xGa_{1-x}N$ as cladding layers can enhance the optical confinement in the Er:GaN core region and makes the design of single mode PWG with ease.

[0131] In another embodiment of the present invention, as shown in FIG. **10**, the core-cladding PWG or core-cladding fiber based on Er:GaN of this invention (that includes an Er:GaN core **1001** and Un-GaN Cladding **1002-1003**) can be utilized as a gain medium in an optical amplifier or a laser illuminator **1000**, in which the incoming signal **1005** (around 1.5 μm) can be amplified via a resonant pump **1004** using a 980 nm laser diode to an amplified output beam **1006** (around 1.5 μm).

[0132] In another embodiment of the present invention, as shown in FIG. **11**, the core-cladding PWG or core-cladding fiber **1101** based on Er:GaN can be utilized as a gain medium in a high energy laser **1100**, which is capable to provide lasing emission **11002** near 1.5 μm via a resonant pump **1103** using a 980 nm laser diode or laser diode stack. Previous results have also indicated that other possible pump lines in Er:GaN are 1514 nm and 1539 nm for a quasi-four-level and quasi-three-level system, respectively, whereas the lasing emission lines are most likely to occur at 1569 nm and 1581 nm, conforming to the requirements of an extremely small quantum defect lasing system. Thus, the resonant pumping source can also be a 1514 nm or a 1539 nm laser diode or laser diode stack. Pumped by a 1514 nm laser, the GaN/Er:GaN/GaN core-cladding PWGs HELs can provide lasing emission in the retina-safe spectral region with a high quantum efficiency and extremely low quantum defect.

[0133] While embodiments of the invention have been shown and described, modifications thereof can be made by one skilled in the art without departing from the spirit and teachings of the invention. The embodiments described and the examples provided herein are exemplary only, and are not intended to be limiting. Many variations and modifications of the invention disclosed herein are possible and are within the scope of the invention. The scope of protection is not limited by the description set out above, but is only limited by the claims which follow, that scope including all equivalents of the subject matter of the claims.

[0134] The disclosures of all patents, patent applications, and publications cited herein are hereby incorporated herein by reference in their entirety, to the extent that they provide exemplary, procedural, or other details supplementary to those set forth herein.

[0135] Amounts and other numerical data may be presented herein in a range format. It is to be understood that such range format is used merely for convenience and brevity and should be interpreted flexibly to include not only the numerical values explicitly recited as the limits of the range, but also to include all the individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly recited. For example, a numerical range of approximately 1 to approximately 4.5 should be interpreted to include not only the explicitly recited limits of 1 to approximately 4.5, but also to include individual numerals such as 2, 3, 4, and sub-ranges such as 1 to 3, 2 to 4, etc. The same principle applies to ranges reciting only one numerical value, such as "less than approximately 4.5," which should be interpreted to include all of the above-recited values and ranges. Further, such an interpretation should apply regardless of the breadth of the range or the characteristic being described.

[0136] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood to one of ordinary skill in the art to which the presently disclosed subject matter belongs. Although any methods, devices, and materials similar or equivalent to those described herein can be used in the practice or testing of the presently disclosed subject matter, representative methods, devices, and materials are now described.

[0137] Following long-standing patent law convention, the terms "a" and "an" mean "one or more" when used in this application, including the claims.

[0138] Unless otherwise indicated, all numbers expressing quantities of ingredients, reaction conditions, and so forth used in the specification and claims are to be understood as being modified in all instances by the term "about." Accordingly, unless indicated to the contrary, the numerical parameters set forth in this specification and attached claims are approximations that can vary depending upon the desired properties sought to be obtained by the presently disclosed subject matter.

[0139] As used herein, the term "about" and "substantially" when referring to a value or to an amount of mass, weight, time, volume, concentration or percentage is meant to encompass variations of in some embodiments ±20%, in some embodiments ±10%, in some embodiments ±5%, in some embodiments ±1%, in some embodiments ±0.5%, and in some embodiments ±0.1% from the specified amount, as such variations are appropriate to perform the disclosed method.

[0140] As used herein, the term "and/or" when used in the context of a listing of entities, refers to the entities being present singly or in combination. Thus, for example, the phrase "A, B, C, and/or D" includes A, B, C, and D individually, but also includes any and all combinations and subcombinations of A, B, C, and D.

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1. (canceled)

2. (canceled)

3. A core-cladding planar waveguide (PWG) structure comprising:
- (a) a core layer comprising Er:GaN, wherein the core layer has a uniform Er doping concentration;
- (b) a first GaN layer comprising undoped GaN, and
- (c) a second GaN layer comprising undoped GaN, wherein the core layer is between the first GaN layer and the second GaN layer.
- (d) a first transition layer that is between a first side of the first GaN layer and a first side of the core layer, wherein
  - (i) a first side of the first transition layer is adjacent the first side of the first GaN layer,
  - (ii) a second side of the first transition layer is adjacent the first side of the core layer, and
  - (iii) Er doping of the first transition layer is increasing in concentration from the first side of the first transition layer to the second side of the first transition layer; and
- (e) a second transition layer that is between a first side of the second GaN layer and a second side of the core layer, wherein
  - (i) a first side of the second transition layer is adjacent the second side of the core layer,
  - (ii) a second side of the second transition layer is adjacent the first side of the second GaN layer, and
  - (iii) Er doping of the second transition layer is decreasing in concentration from the first side of the second transition layer to the second side of the second transition layer.

4. The core-cladding PWG structure of claim **3**, wherein
- (a) the Er doping of the first transition layer is increasing from a concentration of 0 at the first side of the first transition layer to the Er doping concentration of the core layer at the second side of the first transition layer; and
- (b) the Er doping of the second transition layer is decreasing from the Er doping concentration of the core layer at the first side of the second transition layer to a concentration of 0 at the second side of the second transition layer.

5. The core-cladding PWG structure of claim **4**, wherein the uniform Er doping of the core layer has a concentration of at least 1×10^{18} atoms/cm^3.

6. The core-cladding PWG structure of claim **4**, wherein the uniform Er doping of the core layer has a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

7. The core-cladding PWG structure of claim **3**, wherein the uniform Er doping of the core layer has a concentration of at least 1×10^{18} atoms/cm^3.

8. The core-cladding PWG structure of claim **3**, wherein the uniform Er doping of the core layer has a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

9. The core-cladding PWG structure of claim **3**, wherein the uniform Er doping of the core layer has a concentration between 1×10^{19} atoms/cm^3 and 1×10^{21} atoms/cm^3.

10. The core-cladding PWG structure of claim **3**, wherein the core-cladding PWG structure is a GaN/Er:GaN/GaN core-cladding PWG structure.

11. The core-cladding PWG structure of claim **3**, wherein the core layer is co-doped with Er and Yb.

12. The core-cladding PWG structure of claim **11**, wherein the Er and Yb doping of the core layer has a concentration between 1×10^{18} atoms/cm^3 and 1×10^{22} atoms/cm^3.

13. The core-cladding PWG structure of claim **3**, wherein the core layer has a thickness of at least 5 μm.

14. The core-cladding PWG structure of claim **3**, wherein in the core-cladding PWG structure is a strip having a longitudinal axis.

15. The core-cladding PWG structure of claim **14**, wherein in the core-cladding PWG structure has a waveguide width that is at most ⅕ the length of the strip along the longitudinal axis.

16. (canceled)

17. (canceled)

18. A core-cladding planar waveguide (PWG) structure comprising:
- (a) a core strip comprising Er:GaN, wherein
  - (i) the core strip has a longitudinal axis, and
  - (ii) the core strip has a uniform Er doping concentration; and
- (b) a GaN layer of undoped GaN that surrounds the core strip along the longitudinal axis; and
- (c) a transition layer that is between the GaN layer and the core strip, wherein
  - (i) a first side of the transition layer is adjacent the GaN layer along the longitudinal axis;
  - (ii) a second side of the transition layer is adjacent the core strip; and

(iii) Er doping of the transition layer is increasing in concentration between the first side of the transition layer to the second side of the transition layer.

19. The core-cladding PWG structure of claim **18**, wherein the Er doping of the transition layer is increasing from a concentration of 0 at the first side of the transition layer to the Er doping concentration of the core stripe at the second side of the transition layer.

20-63. (canceled)

64. A core-cladding planar waveguide (PWG) structure comprising:

(a) a core strip comprising Er:GaN, wherein

(i) the core strip has a longitudinal axis, and

(ii) the core strip has a uniform Er doping concentration; and,

(b) a first layer of $Al_xGa_{1-x}N$ that surrounds the core strip along the longitudinal axis, wherein x is between 0 and 1, inclusive; and

(c) a transition layer between the core strip and the first layer, wherein the transition layer has an Er doping concentration that increases between (i) a first surface of the first transition layer adjacent to the first layer, and (ii) a second surface of the transition layer adjacent the core strip.

65. The device of claim **64**, wherein the core-cladding waveguide (PWG) structure is a gain medium in the device.

66. The device of claim **65**, wherein the device is selected from a group consisting of optical amplifiers, laser illuminators, and high-energy lasers.

67. The device of claim **66**, wherein the device is operable to operate in a retina safe window.

68. The device of claim **66**, wherein the device further comprises a resonant pump.

69. The device of claim **65**, wherein the core-cladding PWG structure has a core region operable to have an optical confinement of at least 96%.

70. The device of claim **69**, wherein the core-cladding PWG structure has a core region operable to have an optical confinement between 96% and 99%.

71. The device of claim **69**, wherein the core-cladding PWG structure has a core region operable to have an optical confinement of at least 99%.

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