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Carlson et al.

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[54] **DIODE LASER ARRAY**

[75] Inventors: **Nils W. Carlson**, Lawrenceville; **Gary A. Evans**, Robbinsville; **Charlie J. Kaiser**, Trenton, all of N.J.

[73] Assignee: **David Sarnoff Research Center, Inc.**, Princeton, N.J.

[21] Appl. No.: **400,108**

[22] Filed: **Aug. 29, 1989**

[51] **Int. Cl.**[5] **G01C 3/08**; H01S 3/00; H01S 3/08; G02F 1/00

[52] **U.S. Cl.** **356/5**; 330/4.3; 372/50; 372/96; 455/613

[58] **Field of Search** 372/50, 96; 455/613; 356/5; 330/4.3

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Primary Examiner—Stephen C. Buczinski
Attorney, Agent, or Firm—W. J. Burke

[57] **ABSTRACT**

A diode laser array comprises a substrate of a semiconductor material having first and second opposed surfaces. On the first surface is a plurality of spaced gain sections and a separate distributed Bragg reflector passive waveguide at each end of each gain section and optically connecting the gain sections. Each gain section includes a cavity therein wherein charge carriers are generated and recombine to generate light which is confined in the cavity. Also, the cavity, which is preferably a quantum well cavity, provides both a high differential gain and potentially large depth of loss modulation. Each waveguide has a wavelength which is preferably formed by an extension of the cavity of the gain sections and a grating. The grating has a period which provides a selective feedback of light into the gain sections to supporting lasing, which allows some of the light to be emitted from the waveguide normal to the surface of the substrate and which allows optical coupling of the gain sections. Also, the grating period provides an operating wavelength which is on the short wavelength side of the gain period of the gain sections required for laser oscillation. An RF pulse is applied so as to maximize the magnitude of the loss modulation and the differential gain in the gain sections. The array is operated by applying a DC bias to all the gain sections at a level just below the threshold of the gain sections to only one of the gain sections which raises the bias in all of the gain sections to a level that causes all of the gain sections to oscillate. Thus, a small bias can turn the array on and off.

20 Claims, 4 Drawing Sheets

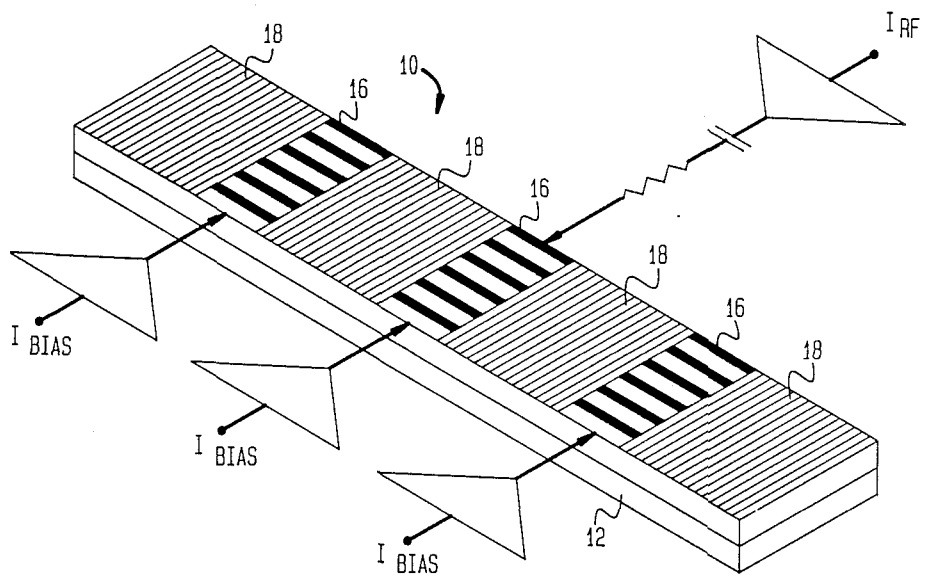


FIG. 1

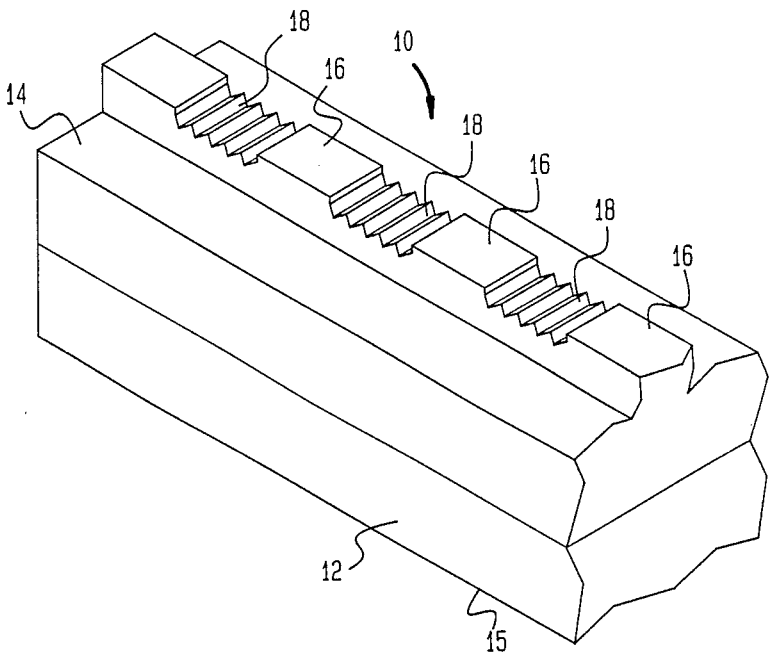
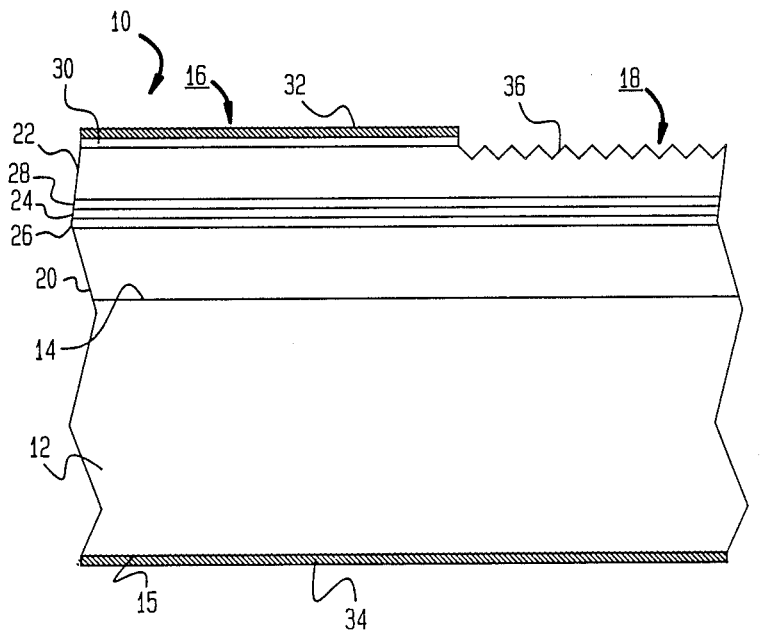

18
10
16
14
18
16
18
16
12
15

FIG. 2


10
30
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34

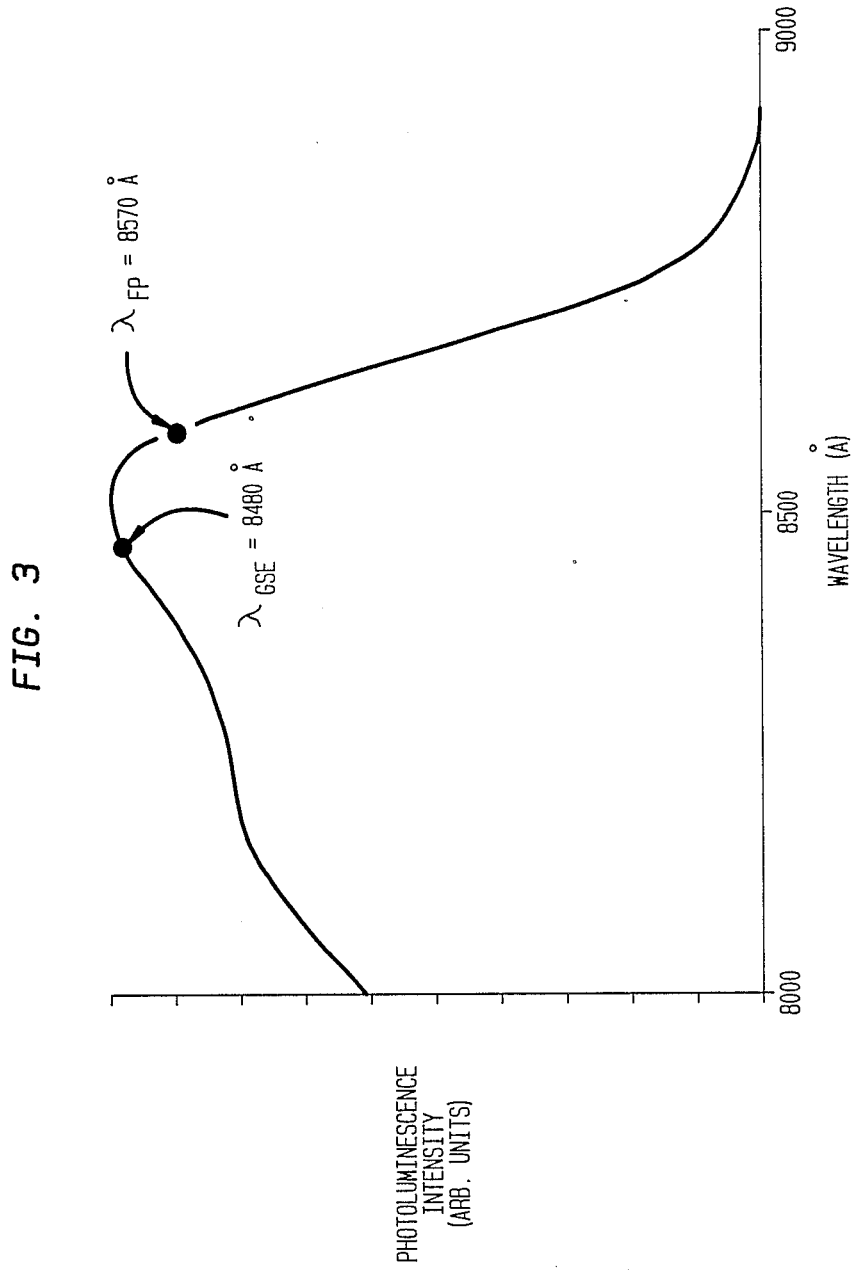

λ_{FP} = 8570 Å
λ_{GSE} = 8480 Å
8000
8500
9000
WAVELENGTH (Å)
PHOTOLUMINESCENCE INTENSITY (ARB. UNITS)

FIG. 3

FIG. 4

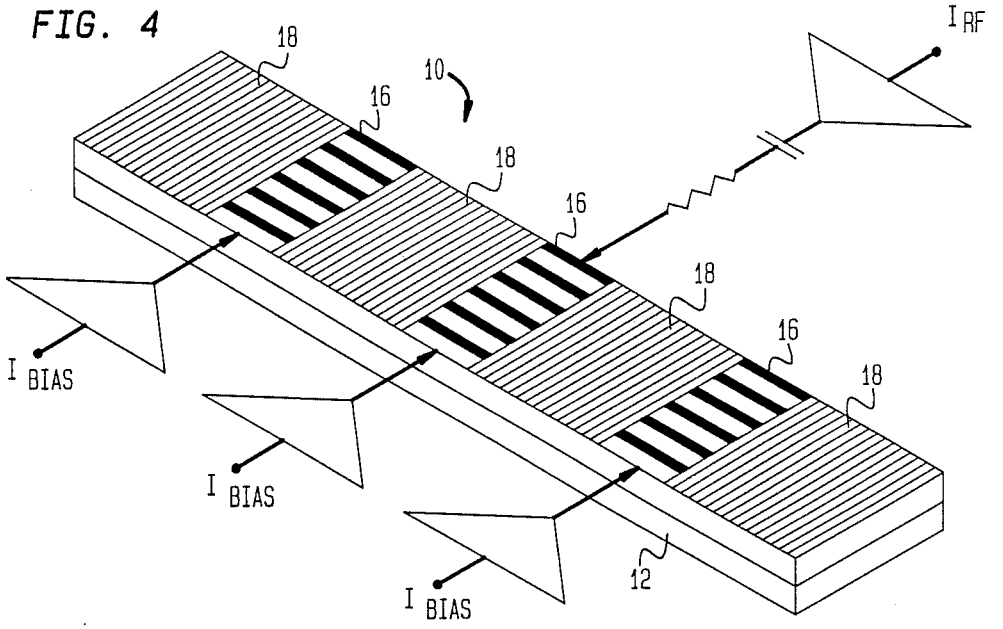

I RF
18
10
16
18
16
18
16
18
I BIAS
I BIAS
I BIAS
12

FIG. 5

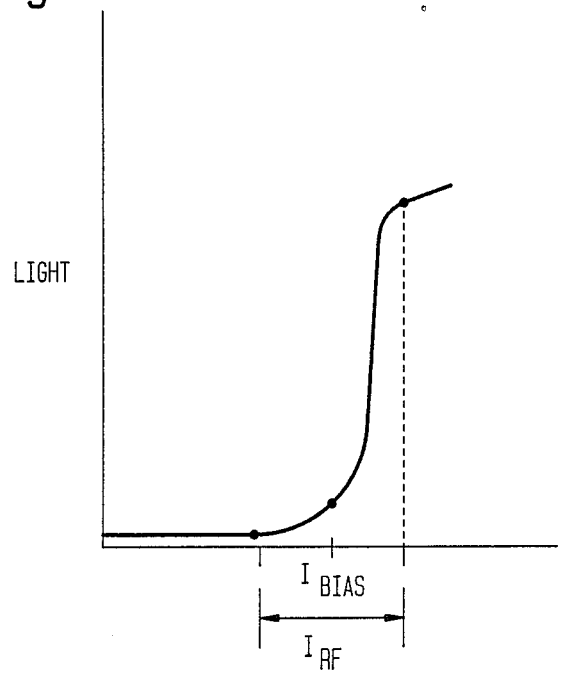

LIGHT
I BIAS
I RF
CURRENT TO MIDDLE GAIN SECTION

FIG. 6

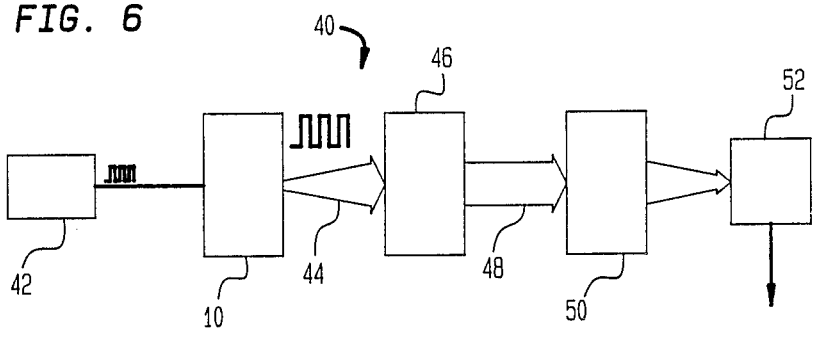
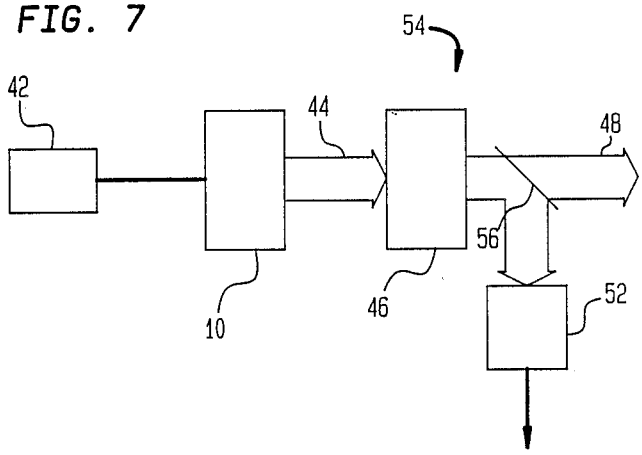


FIG. 7



DIODE LASER ARRAY

The invention described herein was made in the performance of work under NASA Contract No. NAS1-18525 and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958 (72 Stat, 435; 42 U.S.C. 2457).

FIELD OF THE INVENTION

The present invention relates to a semiconductor diode laser array, and, more particularly, to an injection coupled surface emitting semiconductor diode laser array which can operate as an electro-optic amplifier, and has high speed switching characteristics.

BACKGROUND OF THE INVENTION

In free space optical communication systems, diode lasers are attractive as a source of light because of their small size and relatively high efficiency. A diode laser, in general, is a body of a semiconductor material which when biased emits light through the recombination of oppositely charged carriers. The body generally includes regions of opposite conductivity type, which when properly biased, inject charge carriers of one conductivity type from one of the regions into the other where the light generating recombination occurs. Diode lasers in general include a cavity which confines both the charge carriers and the generated light. Also, at the ends of the cavity the light is reflected in a manner so as to generate a beam of substantially coherent light which is generally emitted from an edge of the diode.

Since most single-emitter diode lasers have large angular beam divergences, generally greater than 10°, large collimation telescopes are necessary to form the appropriate communications beam, which is typically about 20 cm. in diameter. This large beam diameter is required for free space optical links because typical propagation distances are on the order of 10,000 km. and the diameter of the **35** receiving telescope is about 10 cm. in diameter. These constraints dictate that the optical transmitter for such a link must have a power output of 500 mW or more in a narrow divergence diffraction limited single lobed far field. Stable single spectral and spatial mode operation are also required, and this stability must be maintained at multi-GHz modulation rates. Single element diode lasers operating in a single mode are limited to operating powers of about 100 mW. Therefore, suitable coherent diode laser arrays which contain a plurality of the diode lasers are necessary to provide the desired power and radiant intensity of the beam which is needed for free space optical communication systems.

A type of diode laser array which has been recently developed is a coherent monolithic array of injection-coupled grating surface emitting (GSE) diode lasers. An array of GSE diode lasers, in general, comprises on a single substrate of a semiconductor material a plurality of electrically isolated gain sections that are within a network of distributed Bragg reflector (DBR) passive waveguides. The gain sections contain regions of opposite conductivity type and a cavity in which the charge carriers of opposite conductivity type are formed and recombine to generate light. The DBR sections function in a three-fold manner. The second grating order of the DBR provides wavelength selection and feedback necessary to support laser oscillation. In first order, the grating couples light out normal to the substrate surface. Finally, the transmissivity of the DBR sections are sufficiently large so as to couple adjacent gain sections. It has been found that GSE arrays can have output powers in excess of **1**

W, far field beam divergence of 1° by 0.01° and spectral outputs narrower than 0.25 Angstroms. One such DBR array is shown and described in the article of G.A. Evans et al entitled "Coherent, monolithic two-dimensional (10×10) laser arrays using grating surface emission", published in APPLIED PHYSICS LETTERS, Vol 53(22) Nov. 28, 1988, pgs. 2123-2125. However, for optical communication purposes, it is necessary to be able to switch this type of array at relatively high speeds. Therefore, it is desirable to have GSE array which not only can provide high power output, but which can be switched relatively fast for communication purposes.

SUMMARY OF THE INVENTION

A diode laser array comprises a substrate of a semiconductor material having a major surface. A plurality of gain sections are in said major surface. Each of the gain sections as a cavity therein for generating light and which can provide both a high differential gain and electrically large depth of loss modulation. A distributed Bragg reflector waveguide is at each end of each gain section and optically connects the gain sections. Each Bragg reflective waveguide has a period to provide an operating wavelength which is on the short wavelength side of the gain peak of the gain sections. Means is provided to apply a DC bias to each of the gain sections and means is provided to apply modulation pulse to one of the gain sections to switch the array to its light emitting condition.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a top view of one form of a diode laser array of the present invention;

FIG. **2** is a sectional view taken along line **2—2** of FIG. **1**;

FIG. **3** is a curve showing the photoluminescence spectrum of a single quantum well active/waveguide layer of an array of the present invention;

FIG. **4** is a schematic showing of the array illustrating the manner of operating the array;

FIG. **5** is a graph showing the manner that the array operates upon being biased;

FIG. **6** is a schematic diagram of a typical free space optical communication system using the laser array of the present invention; and

FIG. **7** is a schematic diagram of a typical optical radar system using the laser array of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

Referring initially to FIG. **1**, there is shown one form of the diode laser array **10** of the present invention. The array **10** comprises a substrate **12** having first and second opposed surfaces **14** and **15**. On the first surface **14** are a plurality of spaced gain sections **16** arranged in a line. At each end of each gain section **16** is a distributed Bragg reflector (DBR) waveguide **18**. A separate DBR waveguide extends between each pair of adjacent gain sections **16** so as to optically connect them. Although in FIG. **1**, the array **10** is shown as having three gain sections **16** and three DBR waveguides **18**, it can have any

number of the gain sections **16** so long as there are at least two gain sections **16** with a DBR waveguide at each end of each gain section **16**. Also, the gain sections **16** may be arranged in a plurality of lines as long as there is provided means for optically connecting the lines of gain sections together.

As shown in FIG. **2**, each gain section **16** is in the form of a diode laser. As shown, each diode laser gain section **16** comprises a pair of clad layers **20** and **22** of a semiconductor material with the clad layers **20** and **22** being of opposite conductivity types. Thus, if the clad layer **20** is of P-type conductivity, the clad layer **22** is of N-type conductivity. Between the two clad layers **20** and **22** is a thin quantum well layer **24** of a semiconductor material which is undoped. A description of quantum well lasers can be found in the article of Y. Arakawa entitled "Quantum Well Lasers-Gain, Spectra, Dynamics", published in IEEE JOURNAL OF QUANTUM ELECTRONICS, Vol. QE-22, No. 9, September 1986, pgs. 1887–1986; . The clad layers **20** and **22** are of a material having an energy band-gap higher than that of the material of the quantum well layer **24** so as to achieve both charge carrier and light confinement within the quantum well layer **4**. For example, the clad layers **20** and **22** may be of aluminum gallium arsenide wherein the mole fraction of aluminum arsenide is about 70% ($Al_{.7}Ga_{.3}$), and the quantum well layer **24** may be of gallium arsenide. Between the quantum well layer **24** and each of the clad layers **20** and **22** is a confinement layer **26** and **28** respectively, each of which is of the same conductivity type as its adjacent clad layer. The confinement layers **26** and **28** are of aluminum gallium arsenide and may be graded so that the mole fraction of aluminum arsenide is varies from that of the clad layers **20** and **22** at the clad layers to about one-half of that in the clad layers **20** and **22** at the quantum well layer **24**. Thus, the composition of graded confinement layers **26** and **28** would vary from $Al_{.7}Ga_{.3}$ at the clad layers **20** and **22** to $Al_{.7}Ga_{.3}$ at the quantum well layer **24**. However, the confinement layers **26** and **28** may be of uniform composition having an energy band-gap between that of the materials of the clad layers **20** and **22** and the quantum well layer **24**,

such as $Al_{.7}Ga_{.3}$.

A capping layer **30** is over the outermost clad layer **22**. The capping layer **30** is of a semiconductor material of the same conductivity type as that of the clad layer **22**, i.e. P-type conductivity. The capping layer is preferably of gallium arsenide. The substrate **12** is of a conductivity type the same as that of the clad layer **20**, i.e. N-type conductivity. The substrate **12** can be of any semiconductor material on which the gain regions **16** and DBR waveguide regions **18** can be formed, such as gallium arsenide. Typically the clad layers **20** and **22** are of a thickness of about 1.2 micrometers, the quantum well layer is of a thickness of about 50 to 100 Angstroms, the confinement layers **26** and **28** are of a thickness of about 0.2 to 0.4 micrometers, and the capping **30** layer is of a thickness of about 0.2 micrometers. A contact layer **32** of a conductive material is on and makes ohmic contact with the capping layer **30**. A contact layer **34** of a conductive material is on and makes ohmic contact with the second surface **15** of the substrate **12**.

Each of the DRB waveguides **18** comprises extensions of the clad layers **20** and **22**, the quantum well layer **24** and the graded layers **26** and **28** of the gain sections **16**. To improve performance, the thickness of the quantum well layer in the waveguide **18** may be different than that of the gain section **16** or the quantum well layer in the waveguide could be partially disoriented. However, the DBR waveguides **18** do not include the capping layer **30** or the contact layer **32**. Instead, in the surface of the outermost clad layer **22** is a grating. As shown the grating is formed by a plurality of parallel V-shaped grooves **36** extending transversely across the clad layer **22**. The number and dimensions of the grooves **36** are such as to form a second order grating. For example, the grooves **36** may have a period of about 2500 angstroms. However, the waveguide **18** may have any other type of grating formed therein. Also, the clad layer **22** in the DBR **18** is thinner than in the gain section **20**, being about 0.1 micrometers in thickness. Each of the DBR waveguides **18** and gain sections **16** are typically several hundred micrometers in length. In the waveguides, the quantum well layer **24** serves as a waveguide and the clad layers **20** and **22** and the confinement layers **26** and **28** serve to confine the light in the quantum well waveguide layer **24**.

As shown in FIG. **4**, the diode laser array **10** is operated by applying a DC bias (I_{Bias}) to each of the gain sections **16**. As indicated in FIG. **5**, this bias is less than that necessary to cause the gain sections **16** to oscillate and thereby generate light. A modulation pulse, such as an RF bias (I_{RF}), is then applied to one of the gain sections **16**. As shown in FIG. **5**, this additional bias is sufficient to drive the one gain section **16** such that saturation of loss occurs. This lowers the round trip loss in the entire array so as to turn on all of the gain sections **16** and thereby cause the gain sections **16** to oscillate in a mutually coherent fashion. By having the DC bias applied to the gain sections **16** very close to their threshold voltage, only a small RF bias is necessary to one of the gain sections **16** to turn on all of the gain sections **16**. It has been found that the DC bias can be applied to the gain sections **16** such that the optical power output from all of the gain sections **16** is greater than the small RF bias needed to turn them on. Thus, the device **10** acts as an electro-optical amplifier.

Since the diode laser array **10** can be operated by a small pulse, only a small power source is required for the operation of the array **10**. By using gain sections **16** which have a high differential gain, the array **10** can be quickly turned on and off.

In order for the array **10** to achieve both high speed switching and short output pulses, it is necessary that the gain sections **16** have suitably strong saturable optical loss as well as a carrier dependent optical loss at certain wavelengths. Quantum well active layers provide both of these conditions. Although the gain sections **16** of the array **10** have been shown as being single quantum wells, they can alternatively be multiple quantum wells. Also, although the array has been described as being operated by a RF pulse, any modulation of the one section which increases the bias thereon, such as a DC pulse, can be used.

The DBR waveguide **18** serves three functions. The second grating order provides wavelength selective feedback of the light generated in the gain sections **16** which is necessary to support laser oscillation in the gain sections **16**. Secondly, the first grating order couples light out of the amplifier **10** normal to the surface **14** of the substrate **12** so as to achieve emission of light from all of the DBR waveguides **18**. Thirdly, the transmissivity of the DBR waveguide **18** must be sufficiently high so that light passes through the waveguide **18** from

one gain region **16** to the next so that adjacent gain sections **16** are optically coupled. In addition, the grating period of the DBR waveguides **18** should be such that the operating wavelength of the device is on the short wavelength side of the gain peak of the gain sections **16** so that the magnitude of the loss modulation and the differential gain of the gain sections **16** is maximized.

The nominal operating wavelength of a grating-surface-emitting laser array is determined by satisfying the Bragg condition for the grating in the DBR waveguides **18**. The Bragg wavelength is equal to the grating period times the effective index of the spatial mode in the DBR waveguide **18**. Wavelengths within the reflectivity bandwidth of the DBR waveguide will be retro-reflected back into the gain sections so that laser oscillation of the array only occurs inside this small bandwidth centered on the Bragg wavelength of the waveguide region. Therefore, with a knowledge of the gain spectrum and waveguide effective index, it is possible to select a specific operating wavelength by appropriate choice of the grating period. An example of how the operating wavelength of an array can be set to the short wavelength side of the peak of the gain spectrum is shown in FIG. **3**. Here the photoluminescence spectrum of a single quantum well structure of the type shown in FIG. **2** of an array **10** is shown. The peak of the quantum well photoluminescence spectrum (which is about 8510 Angstroms for the spectrum shown in FIG. **3**) corresponds closely to the peak of the gain spectrum However, a grating period of 2584 Angstroms results in an operating wavelength of 8480 Angstroms, which is about 30 Angstroms to the short wavelength side of the peak of the photoluminescence.

Referring to FIG. **6** there is shown a schematic diagram of a typical free air optical communication system **40** which utilizes the diode laser array **10** of the present invention. The laser array **10** is fed from a power source **42** capable of providing a series of modulated pulses, such as RF pulses. The array **10** emits pulses of light **44** of a power greater than the amplitude of the input pulses from the power source **42**. The pulsed light beam **44** is directed into a transmitting telescope **46** which collimates the light and directs it as a beam **48** in a desired direction. The beam **48** is picked up by a receiving telescope **50** which directs it into an optical detector **52**. The optical detector **52** coverts the pulsed beam of light into electrical pulses which are fed to a receiving circuit, not shown. By varying the amplitude of, the spacing between and/or length of the electrical pulses fed to the array **10**, information can be communicated through the system **40**.

Referring to FIG. **7**, there is schematically shown an optical radar system **54** which utilizes the diode laser array **10** of the present invention. In the radar system **54**, like in the communication system **40**, the laser array **10** is fed by a power source **42** which provides modulation pulses to the array **10**. The pulses of light **44** from the array **10** are feed into a transmitting telescope **46** which directs a beam of pulsed light **48** through a beam splitter **56** to an object to be detected, not shown. The beam splitter **56** also directs some of the emitted beam **48** to an optical detector **52**. The light that is directed toward the object is reflected back and is also directed into the optical detector **52** by the beam splitter **56**. By comparing the portion of the original beam and the returned beam, the optical detector can determine the distance to the object or other information regarding the object as is well known in radar systems.

Thus, there is provided by the present invention a diode laser array **10** in which a small bias can turn on all of the gain sections **16** so as to achieve the emission of light of high power from all of the DBR waveguides **18**. This allows the array **10** to be quickly turned on and off so that it can be used for communication purposes. In addition, since the optical power out is greater than the bias needed to operate the array **10**, the array **10** operates as an electro-optical amplifier. Although the array **10** has been shown as described as comprising a line of the gain sections **16**, the array can also be formed of a plurality of the lines of gain sections **16** which are arranged in a two dimensional array of rows and columns

What is claimed is:

1. A diode laser array comprising:

a substrate of a semiconductor material having first and second opposed surfaces;

a plurality of spaced gain sections on the first substrate surface, each of said gain sections having a cavity therein for generating light and which can provide both a high differential gain and potentially large depth of loss modulation;

a distributed Bragg reflector passive waveguide at each end of each gain section and optically coupling said gain sections, said waveguides having a grating period to provide an operating wavelength which is on the short wavelength side of the gain peak of the gain sections;

means for applying a DC bias to each of said gain sections; and

means for applying a modulation pulse to only one of the gain sections.

2. An array in accordance with claim **1** in which the modulation pulse is a RF pulse.

3. An array in accordance with claim **1** in which each of the gain sections includes a semiconductor quantum well region.

4. An array in accordance with claim **3** in which each of the gain sections comprises a pair of clad layers of a semiconductor material of opposite conductivity types with the quantum well region being between the clad layers.

5. An array in accordance with claim **4** in which each of the clad layers is of a semiconductor material having an energy band-gap greater than that of the semiconductor material of the quantum well region.

6. An array in accordance with claim **5** in which each of the gain sections includes a confinement layer between each of the clad layers and the quantum well region, each of the confinement layers being of the same conductivity type as its adjacent clad layer and of a semiconductor material at least a portion of which has an energy band-gap which is between that of its adjacent clad layer and that, of the quantum well region.

7. An array in accordance with claim **6** in which each of the confinement layers is a graded layer in that it is of a material having an energy band-gap which decreases from that of its adjacent clad layer to a level above that of the quantum well region.

8. An array in accordance with claim **6** in which each gain section includes a conductive contact over and electrically connected to each of the outermost of the clad layers and a conductive contact on the second surface of the substrate.

9. An array in accordance with claim **8** in which each gain section includes a capping layer of a semiconduc-

tor material over the outermost of the clad layers, said capping layer being of the same conductivity type as the outermost clad layer, and the conductive contact is on the capping layer.

10. An array in accordance with claim **8** in which each of the waveguides includes a waveguide region between a pair of clad layers and a grating in the outermost of the clad layers.

11. An array in accordance with claim **10** in which the waveguide region of each waveguide is an extension of the quantum well region of the gain sections, and the clad layers are extensions of the clad layers of the gain sections.

12. An array in accordance with claim **11** in which each of the waveguides includes a confinement layer between each clad layer and the waveguide region with the confinement layers being extensions of the confinement layers of the gain sections.

13. An array in accordance with claim **12** in which the grating of each waveguide has a period such that the second grating order provides wavelength selective feedback into the gain sections to support laser oscillation, the first order couples light out of the waveguides normal to the first surface of the substrate, and the transmissivity is sufficient to optically couple adjacent gain sections.

14. A method of operating a diode laser array which includes on a surface of a substrate a plurality of spaced gain sections each having a cavity therein for generating light and which can provide both a high differential gain and potentially large depth of loss modulation, and a distributed Bragg reflection passive waveguide at each end of each gain section and optically coupling the gain section, the waveguides including a grating having a grating period to provide an operating wavelength which is on the short wavelength side of the gain peak of the gain sections, the method comprising the steps of:

applying a bias to all of the gain sections at a level below that of the threshold of the gain sections at which lasing oscillation occurs; and

applying a bias to only one of the gain sections to cause all of the gain sections to oscillate.

15. A method in accordance with claim **14** in which all of the gain sections are biased with a DC bias to a level just below the threshold of the gain sections, and a small modulation pulse is applied to the one gain section to cause all of the gain sections to oscillate.

16. A method in accordance with claim **15** in which the modulation pulse is an RF pulse.

17. In an optical communication system which includes a diode laser array for emitting a pulsed beam of light, a source of power for said array, and an optical detector for receiving the beam of light, said diode laser array comprising:

a substrate of a semiconductor material having first and second opposed surfaces;

a plurality of spaced gain sections on the first substrate surface, each of said gain sections having a cavity therein for generating light and which can provide both a high differential gain and potentially large depth of loss modulation;

a distributed Bragg reflector passive waveguide at each end of each gain section and optically coupling said gain sections, said waveguides having a grating period to provide an operating wavelength which is on the short wavelength side of the gain peak of the gain sections;

means for applying a DC bias to each of said gain sections; and

means for applying a modulation pulse to only one of the gain sections.

18. An optical communication system in accordance with claim **17** including an optical transmission telescope into which the array directs its beam for collimating the beam and directing it toward the detector, and an optical receiving telescope receiving the beam and directing it into the detector.

19. In an optical radar system which includes a diode laser array for generating a pulsed beam of light, means for directing the beam of light toward an object and an optical detector means for receiving the beam reflected from the object, the diode laser array comprising:

a substrate of a semiconductor material having first and second opposed surfaces;

a plurality of spaced gain sections on the first substrate surface, each of said gain sections having a cavity therein for generating light and which can provide both a high differential gain and potentially large depth of loss modulation;

a distributed Bragg reflector passive waveguide at each end of each gain section and optically coupling said gain sections, said waveguides having a grating period to provide an operating wavelength which is on the short wavelength side of the gain peak of the gain sections;

means for applying a DC bias to each of said gain sections; and

means for applying modulation pulses to only one of the gain sections.

20. An optical radar system in accordance with claim **19** including an optical transmission telescope into which the array emits its beam for collimating the beam and directing it toward the object, a beam splitter for directing a portion of the emitted beam to the detector and for directing the returned beam to the detector.

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