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Declarations under Rule 4.17:

[Continued on next page]

(54) **Title**: SEMICONDUCTOR LASER

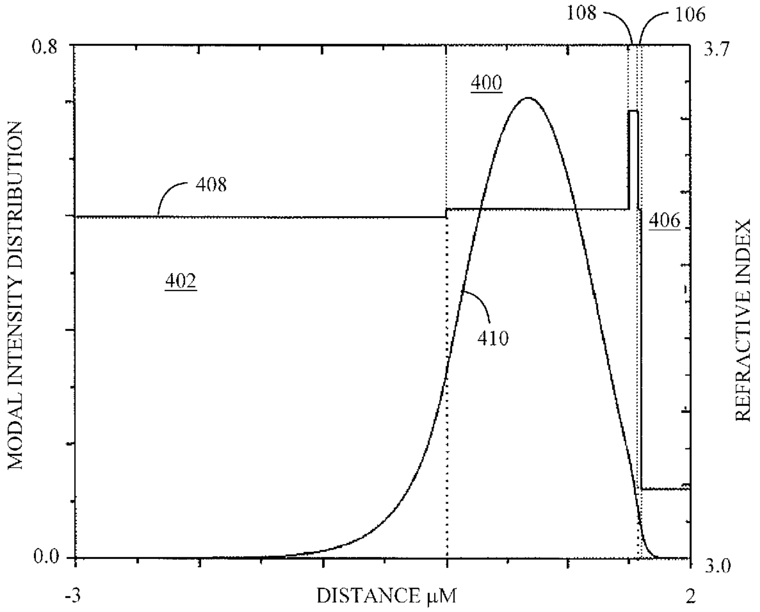

FIG. 4

(57) **Abstract**: A single pulse semiconductor laser operating in the gain- switching regime comprises a plane asymmetric waveguide and an active layer in the waveguide, the ratio of a thickness of the active layer to an optical confinement factor of the laser being extremely large, larger than about 5μm, for example.

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— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

— *with international search report (Art. 21(3))*

Semiconductor laser

Field

The invention relates to a semiconductor laser based on gain switching.

Background

Various applications such as automobile safety devices, laser radars, 3-D imaging, laser tomography, time imaging spectroscopy, etc., require optical sources which generate high-power (10W to 1000W) single optical pulses in the picosecond range.

A high-power single pulse can be produced with a semiconductor laser diode which may have a double heterostructure laser chip. To be commercial, the energy of the optical pulse should be produced by low-cost, compact and reliable electric power sources. Suitable and readily available electric power sources can provide an electric pulse having a duration of a few nanoseconds, a reasonably symmetric shape and an amplitude of order 10A.

There is a need for higher-power optical pulses generated using the low-cost power sources and there have also been attempts to increase the optical power. However, all the attempts have faced serious drawbacks. For example, if the amplitude of the electric current pulse is increased, the power of the optical pulse also increases but after a certain critical value a second optical pulse trailing the primary optical pulse will appear which is highly undesirable. The proposed increase in the volume or dimensions of the active layer may increase the power of the optical pulse but the increase also results in at least one trailing optical pulse. Theoretically, the electric current pulse may be formed such that it has a very sharp trailing end for reducing the probability of a trailing pulse, but that is beyond reach of or at least nontrivial to achieve with the high-power electronics at the moment.

Brief description of the invention

An object of the invention is to provide an improved laser. According to an aspect of the invention, there is provided a single pulse semiconductor laser operating in the gain-switching regime. The laser comprises a plane asymmetric waveguide and an active layer in the waveguide, the ratio of a thickness of the active layer to an optical confinement factor of the laser being larger than about 5μm.

According to another aspect of the invention, there is provided a method of manufacturing a single pulse semiconductor laser operating in the gain-switching regime. The method further comprises forming a plane asymmetric waveguide with an active layer in the waveguide such that the ratio of a thickness of the active layer to an optical confinement factor of the laser is larger than about 5μm.

The invention provides several advantages. The amplitude of the injection current can be high without generating an optical trailing pulse after the main optical pulse.

List of drawings

In the following, the invention will be described in greater detail with reference to the embodiments and the accompanying drawings, in which

Figures 1A and 1 B show a structure of a semiconductor laser;

Figure 2 illustrates transient behaviors of a prior art laser;

Figure 3 illustrates transient behaviors and a trailing optical pulse of a prior art laser;

Figure 4 shows a refractive index and light intensity distribution in a semiconductor laser;

Figure 5 illustrates transient behaviors of a laser with a large spot size;

Figure 6 illustrates transient behaviors of a laser with a slightly smaller spot size than in that in Figure 5; and

Figure 7 illustrates a flow chart of the manufacturing method.

Description of embodiments

With reference to Figures 1A and 1B, examine an example of a semiconductor laser diode based on, for example, aluminum gallium arsenide (AlGaAs). In formulas of AlGaAs it is usual k > x > y > z. The line 10 presents in an arbitrary scale the value of an energy gap Eg between a conduction and a valence band. The laser may be layered in a double heterostructure between electrodes 100, 102, which may receive the electric power fed to the laser during operation. The electrodes 100, 102 may be metal contacts. The wide gap layer 104 may be high-doped p-type for donating excess holes. The structure from a high-doped wide gap layer 112 to the substrate 114 may be n-type for donating negative carriers. A complex narrow gap waveguide layered structure 116, which is an optical cavity for stimulated emission, may comprise layers

106 to 110, and the waveguide 116 may terminate at both ends in reflective surfaces at least one of which may finally transmit the optical pulse outwards. An active layer, where free electrons and holes exist and recombine by stimulated emission during the operation, may comprise the layer 108. The active layer 108 may be clearly much thinner than the whole waveguide 116 but much thicker than 10nm, hence making the laser a bulk or multiple quantum wells (MQWs).

To illustrate the advantages of the proposed device, consider a simple standard lumped rate equation model for the averaged electron density N and photon density S in a semiconductor laser in the form

$$dN/dt = i(t)/eV - N/\tau_n - v_g g(N,S)S, \tag{1}$$

$$dS/dt = v_g(\Gamma_a g(N,S) - \alpha)S + \Gamma_a \beta N/\tau_n, \tag{2}$$

where i is the injection current, e the electron charge, V = dLw is a volume of the active layer, with L the cavity length and w the stripe width and d the thickness of the active layer, $\tau_n(N) = 1 + B_1N/(BN)$ is the carrier lifetime (B being the bimolecular recombination coefficient, and B_1 a correction coefficient taking into account saturation of the recombination rate at high N; for GaAs/AlGaAs material $B \approx 10^{-10}$ cm^3/s and $B1 \approx 10^{-19}$cm^3), Γ_a is an optical confinement factor, v_g is the group velocity of light, $\alpha = \alpha_{out} + \alpha_{in}$ is the total (outcoupling and internal parasitic) cavity losses, and β is the spontaneous emission factor. For the gain-current density relation, a two-parameter logarithmic fit for both quantum well and bulk active layers may be expressed as follows:

$$g(N,S) = G_0 \ln(N/N_0)/(1 + \varepsilon S), \tag{3}$$

where N_0 is the transparency carrier density and G_0 is a gain constant, and ε is the gain compression factor. An output power P of an optical pulse may be calculated from S using the formula:

$$P(t) = [(\hbar\omega/e)Lwd\alpha_{out}S(t)]/\Gamma_a, \tag{4}$$

where $\hbar$ is the Planck constant and ω is a photon energy.

The current profile i(t) is a pulse, which may be described by the expression:

$$i(t) = i_0\{\tanh[(t - 2\tau_f)/\tau_r] - \tanh[(t - 2\tau_f - \tau_p)/\tau_d]\} \quad (5)$$

with τ_p characterizing the pulse duration, τ_r the duration of the rising (leading) front, and τ_d that of the decaying (trailing) front. In our simulations, we took $\tau_r = \tau_d = 0.7$ns, $\tau_p = 2$ns.

An optical confinement factor Γ_a can be defined as an overlap between gain medium and the optical mode. The confinement factor Γ_a of a high power single QW CW operation laser may lie around 0.01.

Figure 2 and 3 present transient behaviors of a prior art quantum well AlGaAs laser. The thickness of the active layer is d = 8 nm, the confinement factor $\Gamma_a = 0.01$, $B = 10^{-10}\text{cm}^3/\text{s}$, $B_1 = 10^{-19}\text{cm}^3$ in both cases. Hence, the equivalent spot size, i.e. the ratio of the active layer to the confinement factor d/Γ_a is 0.8 μm.

The injection current profile 200 means the electric pulse fed through electrodes to the laser structure. The threshold carrier density 202 of the carrier density defines a borderline for the laser to output either a single optical pulse or a plurality of optical pulses. If an actual carrier density transient 204 remains below the threshold carrier density 202 after the optical pulse 208, no trailing optical pulse will appear. However, if an actual carrier density transient 204 rises above the threshold carrier density 202 after the optical pulse 208, a trailing optical pulse will appear. A reference carrier density 206 behavior in the same structure without the stimulated emission can be used to compare the non-equilibrium carrier densities at laser and LED operation. The current pulse amplitude is 0.63A in Figure 2 and 0.66A in Figure 3.

In Figure 2, the laser is pumped with a current pulse 200 with a relatively small amplitude (0.63A) of the injection current 200. The laser transmits a single optical pulse 208 of about 125ps FWHM (Full Width at Half Maximum) and a modest amplitude (2.5W), with a total energy of about 350pJ.

The amplitude of the optical pulse 208 is proportional to the total number (density multiplied by volume) of excess carriers above the threshold value accumulated in the active layer by the time the pulse is emitted. After the pulse 208, the carrier number 204, depleted by the pulse, attempts to recover but does not reach the threshold 202 value again and the optical pulse 208 remains single.

In Figure 3 the injection current pulse 300 amplitude has been increased to 0.66A. The horizontal line is a threshold 302 carrier density for reference. An actual carrier density transient 304 has a response to an optical pulse 308 having a drop compared with a reference carrier density 306 behavior in the same structure without the stimulated emission. The power and energy of the output optical pulse 308 has increased along with the current pulse 300 but a trailing optical pulse 310 has also appeared.

In general, if a current amplitude 300 is increased above a certain critical value, the carrier density, depleted by the initial pulse, recovers over the threshold 302 and at least one trailing optical pulse will appear, which is highly undesirable for practical applications. The current used in Figure 2 is deliberately chosen to be almost exactly this critical value. In Figure 3, where the pumping pulse amplitude in the same laser structure has been increased to 0.03A, the trailing pulse 310 is clearly present.

Theoretically, the trailing optical pulses could be avoided if the electric injection pulse 300 had a very sharp trailing end, which, however, is non-trivial to achieve with nanosecond high-power electronics. Alternatively, one can try to delay the optical pulse generation toward the trailing end of the pumping pulse.

The problem of avoiding trailing pulses appearing while achieving high output pulse energy may be solved by using a laser with a large active layer volume V.

Then, one can apply a high-amplitude current pulse and accumulate a large total number of carriers in the active layer, while keeping the relative excess current over the threshold, and thus the excess carrier density, relatively modest.

In theory, the increase in volume can be achieved by increasing any of the three dimensions. However, high-power lasers tend to have quite broad stripes (for example width may be W = 100μm), and extending width beyond this limit leads to problems in focusing the output light.

Increasing the laser length may improve the pulse energy. Consider now a laser which is 5 mm long but otherwise identical to that of Figure 2. The maximum pulse power achievable may be about 4.3W. However, a longer laser also gives a longer optical pulse and has a lower threshold carrier density than the short laser which decreases the relative excess current, at which the secondary pulses appear and thus is adverse to any improvement in single pulse generation. The maximum single pulse energy may be about 780pJ. This is a modest improvement by a factor of 2.2 compared to the shorter structure, with the laser length increased by a factor of five.

Figure 4 (corresponding Figures 1A and 1B) shows refractive indices 408 of different layers and a modal intensity distribution 410 of radiation in a bulk AlGaAs laser having a thickness of the active layer d = 0.08μm and the confinement factor $\Gamma_a = 0.01$.

The laser structure can be made (radically) asymmetric as follows:

1. The refractive index of the n-doped cladding layer 402 is larger than the refractive index of the p-doped cladding layer 406.

2. The active layer 108 position is very near the p-doped cladding layer 104, 406 and quite far from n-doped cladding layer 112, 402.

The larger the differences the more radical asymmetry can be achieved. Increased asymmetry, in turn, serves as the base for a lower value of the confinement factor Γ_a, which makes the equivalent spot size larger. The thickness of the layer 106 of the waveguide is smaller than the thickness of a part of the layer 110, 400 of the waveguide. The thickness of the layer 106 may be much smaller than that of the layer 110, 400 of the waveguide and/or the thickness of the layer 106 can even be 0μm. The refractive index of the layer 106 may be equal or approximately equal to the refractive index of the layer 110.

The difference in the claddings' refractive indices makes the optical mode eccentric such that the modal intensity distribution 410 extends more to the cladding with a larger refractive index. This eccentricity and shift from the active layer to the p-doped cladding layer decreases the confinement factor Γ_a since the overlap of the active layer, which is the gain medium, and the optical mode can thus be reduced.

A thickness d of the active layer 108 may be larger than 50nm. A thickness of the active layer may be, for example, from 50nm to about 150nm. The width of the part of the asymmetric waveguide layer 110 and other parameters of the waveguide and the cladding layers may be chosen such that the laser operates in a single fundamental transverse mode. The confinement factor Γ_a may be lower than 0.02.

Figure 5 presents a transient behaviour of a bulk AlGaAs laser having a thickness of the active layer d = 0.08μm and the confinement factor $\Gamma_a = 0.01$. Those are the same as in Figure 2, except for the thickness d of the active layer 108 which has been increased by a factor of ten. The injection current profile 500 implies an electric pulse of about 2ns and an amplitude 7.1A. The horizontal line 502 is a threshold of carrier density. An actual carrier density transient 504 drops when the optical pulse is formed. A reference carrier density behavior 506 in the same structure without the stimulated emission does not show such a change.

In the example in Figure 5, an injection current 500 may be about ten times higher than that used in Figure 2, while still maintaining a single optical pulse 508. The amplitude of the optical pulse 508, in turn, may be in an order of magnitude higher than that of Figure 2. In Figure 5, the peak power of the optical pulse 508 is 28W, with duration at FWHM of about 150ps.

Figure 6 corresponds to Figure 5 except that the confinement factor Γ_a has been increased to $\Gamma_a = 0.012$. The injection current pulse 600 has a duration τ_p of about 2ns and an amplitude of 7.1A. The horizontal line 602 is a threshold carrier density. The increase in the confinement factor Γ_a, corresponding to the case of too thin a thickness d of the active layer 108, may lead to an emergency of at least one trailing pulse 610 in addition to the main pulse 608. A reference carrier density behavior is presented with a dotted line 606 and an actual carrier density transient is presented with a line 604 of dots and dashes.

The improvement in the laser power with increasing the active layer thickness may rely on keeping the confinement factor Γ_a small. This may be accomplished by structural arrangements. For a constant injection current i and thickness d, an increase in the confinement factor Γ_a decreases the threshold current, leading to a higher relative excess current and to a danger of trailing pulses appearing. If for the initial confinement factor Γ_a the operating current pulse amplitude corresponded to the critical value for single-pulse generation, any increase in Γ_a will place the current above the critical value leading to an emission of an optical trailing pulse.

In Figure 6, the confinement factor Γ_a has been increased by only a factor of 1.2 compared with the case of Figure 5, and an trailing pulse is already well developed.

Maintaining a small optical confinement factor Γ_a is not a trivial task given a relatively large value of the thickness d. It is not possible in most “standard” laser constructions to operate in a single fundamental transverse mode and requires that a special structure be designed.

Figure 7 illustrates a flow chart of the manufacturing method. In step 700, a plane asymmetric waveguide 116 with an active layer 108 in the waveguide 116 is formed such that the ratio of a thickness of the active layer 108 to a confinement factor of the laser is larger than about 5μm.

Even though the invention has been described above with reference to an example according to the accompanying drawings, it is clear that the invention is not restricted thereto but it can be modified in several ways within the scope of the appended claims.

Claims

1. A single pulse semiconductor laser operating in the gain-switching regime, characterized in that the laser comprises a plane asymmetric waveguide (116) and an active layer (108) in the waveguide (116), the ratio of a thickness of the active layer (108) to an optical confinement factor of the laser being larger than about 5μm.

2. The laser of claim 1, characterized in that the laser is configured to operate in a single fundamental transverse mode.

3. The laser of claim 1, characterized in that a thickness of a part of the waveguide layer (106) between the active layer (108) and the p-doped cladding layer (104, 406) is smaller than a thickness of a part of the waveguide layer (110, 400) between the active layer (108) and the n-doped cladding layer (112, 402).

4. The laser of claim 1, characterized in that the refractive index of the n-doped cladding layer (112, 402) is larger than that of the p-doped cladding layer (104, 406), and a difference between the refractive index of the n-doped cladding layer (112, 402) and a part of the waveguide (116) adjacent to it is much smaller than a difference between the refractive index of the p-doped cladding layer (104, 406) and a part of the waveguide (116) adjacent to it.

5. The laser of claim 1, characterized in that a thickness of the active layer (108) is larger than 50 nm.

6. The laser of claim 1, characterized in that the optical confinement factor is lower than 0.02.

7. The laser of claim 1, characterized in that a thickness of the active layer (108) is 50 nm to about 150 nm.

8. A method of manufacturing a single pulse semiconductor laser operating in the gain-switching regime, characterized by forming a plane asymmetric waveguide (116) with an active layer (108) in the waveguide (116) such that the ratio of a thickness of the active layer (108) to an optical confinement factor of the laser is larger than about 5μm.

9. The method of claim 8, characterized by forming a laser operating in a single fundamental transverse mode.

10. The method of claim 8, characterized by forming a thickness of a part of the waveguide layer (106) between the active layer (108) and the p-doped cladding layer (104, 406) smaller than the thickness of a part of the waveguide layer (110, 400) between the active layer (108) and the n-doped cladding layer (112, 402).

11. The method of claim 8, characterized by forming a refractive index of the n-doped cladding layer (112, 402) larger than a refractive index of the p-doped cladding layer (104, 406), and forming a difference between the refractive index of the n-doped cladding layer (112, 402) and a part of the waveguide (116) adjacent to it much smaller than a difference between the refractive index of the p-doped cladding layer (104, 406) and a part of the waveguide (116) adjacent to it.

12. The method of claim 8, characterized by forming a thickness of the active layer (108) larger than 50 nm.

13. The method of claim 8, characterized by forming the optical confinement factor lower than 0.02.

14. The method of claim 8, characterized by forming the active layer (108) with a thickness between 50 nm and about 150 nm.

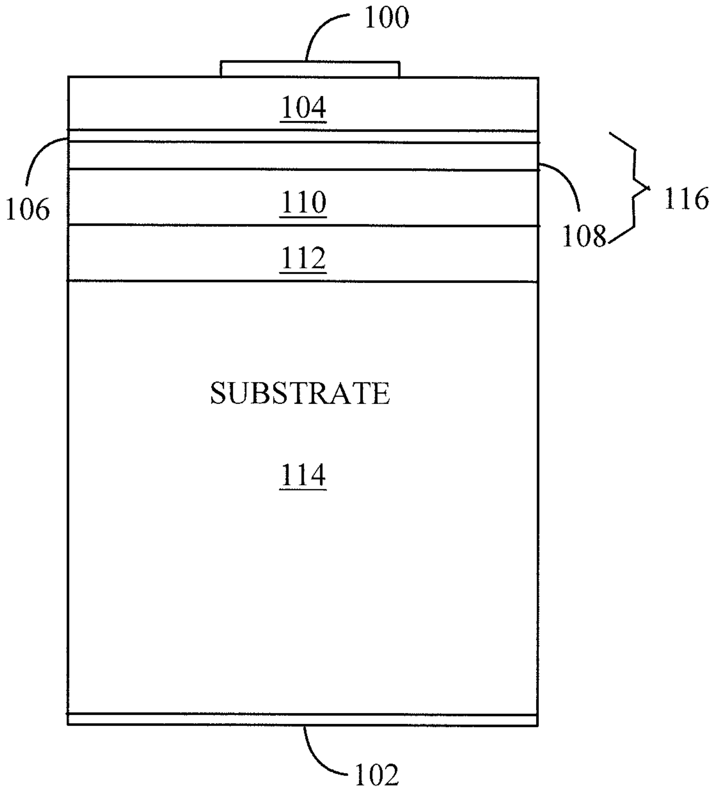

100
104
106
110
108
116
112
SUBSTRATE
114
102

FIG. 1A

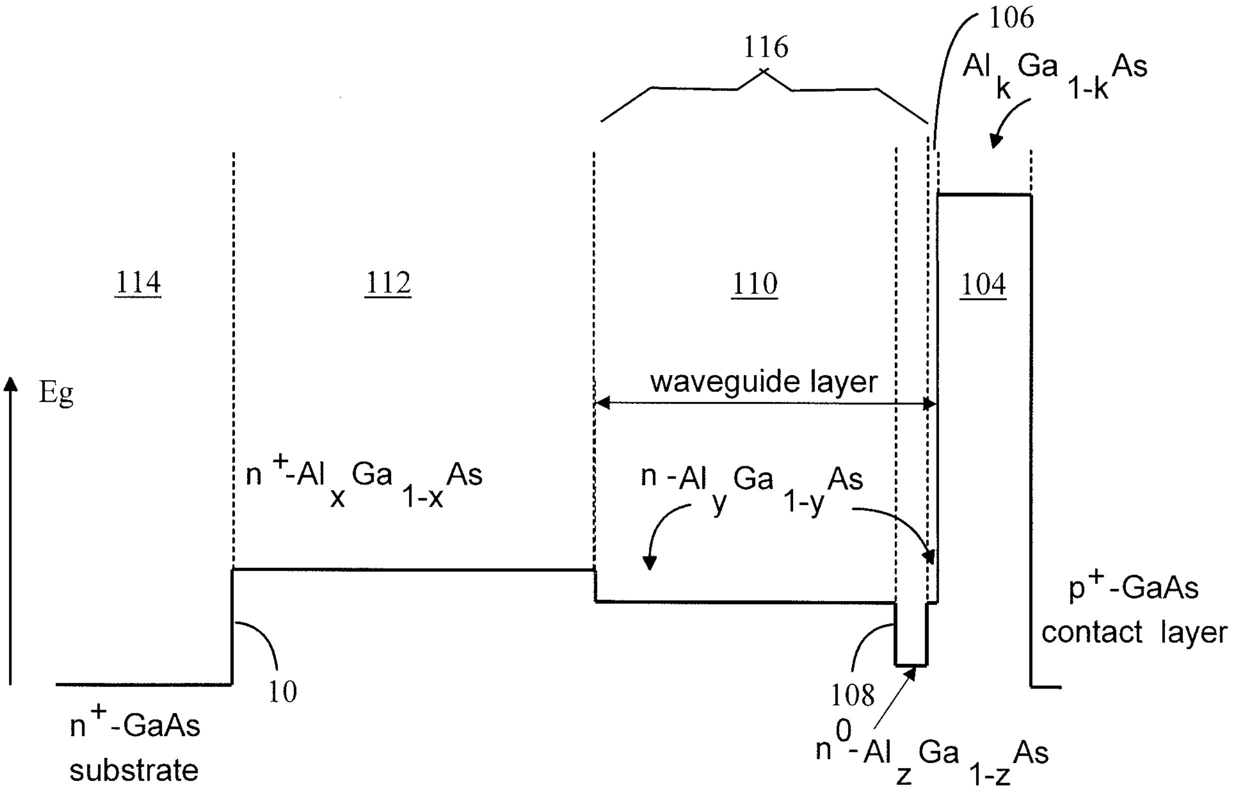
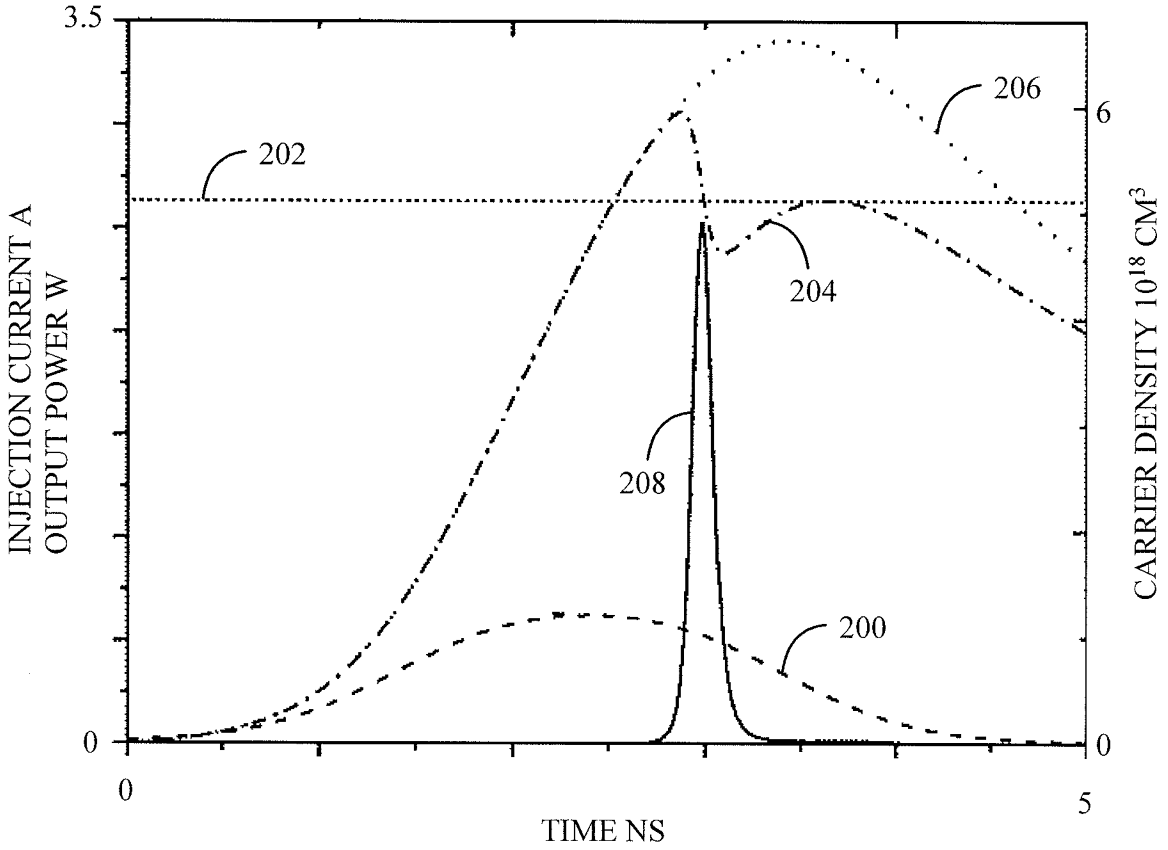

106
116
$Al_kGa_{1-k}As$
114
112
110
104
Eg
waveguide layer
n^+-$Al_xGa_{1-x}As$
n-$Al_yGa_{1-y}As$
p^+-GaAs
contact layer
10
108
n^+-GaAs
substrate
n^0-$Al_zGa_{1-z}As$
bulk active layer

FIG. 1B


3.5
0
6
0
0
5
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206
204
208
200
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OUTPUT POWER W
CARRIER DENSITY 10^{18} CM^3
TIME NS

FIG. 2

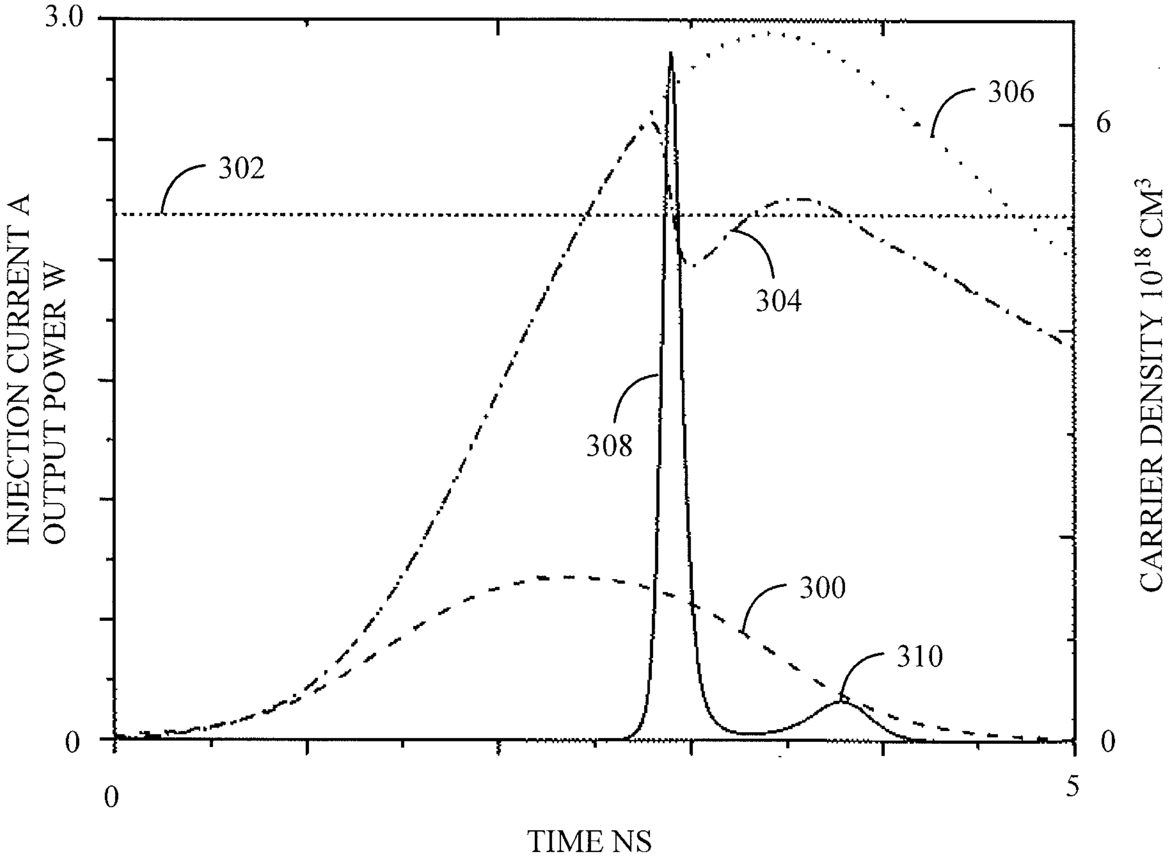

3.0
0
0
5
6
0
INJECTION CURRENT A
OUTPUT POWER W
CARRIER DENSITY 10^{18} CM^3
TIME NS
302
304
306
308
300
310

FIG. 3

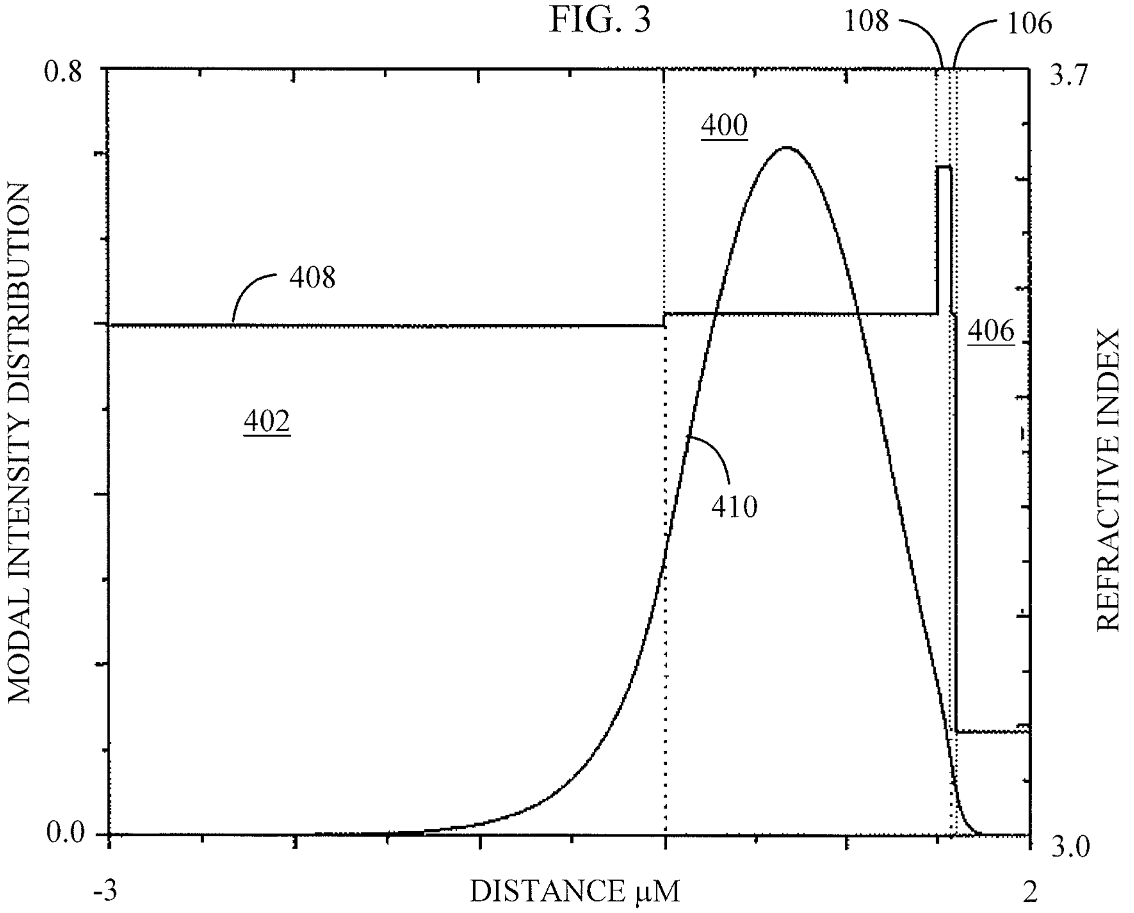
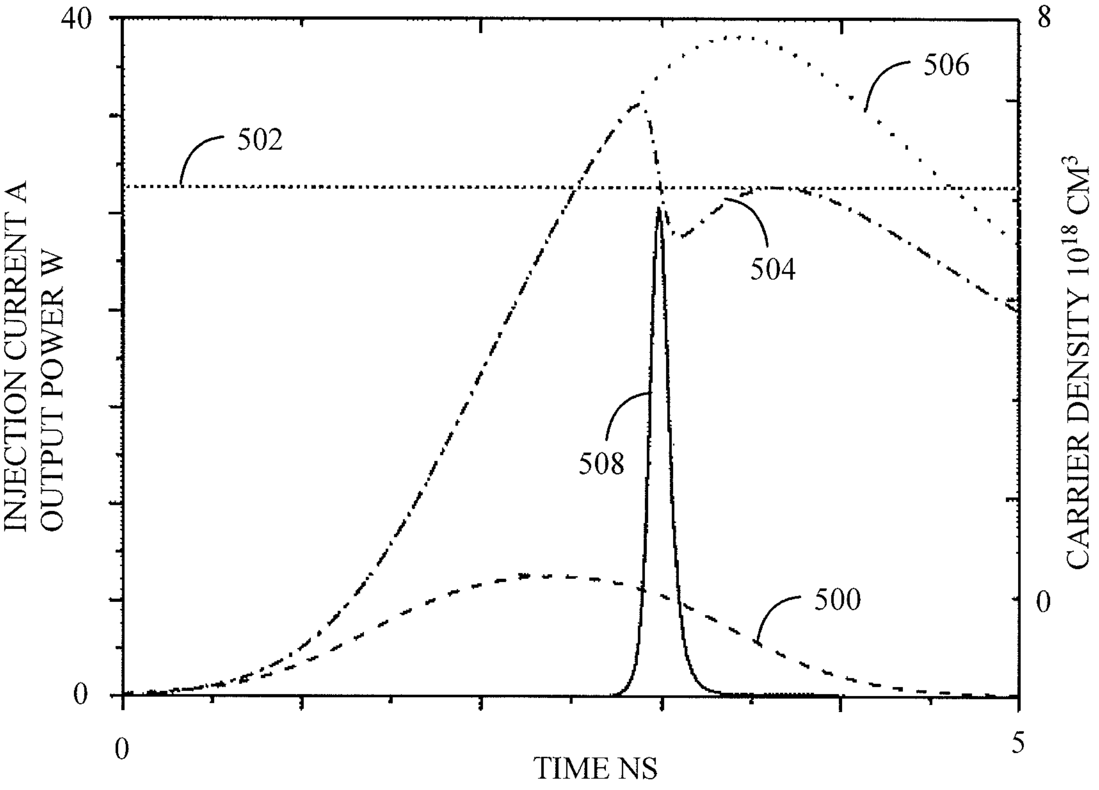

108
106
0.8
0.0
3.7
3.0
-3
2
400
408
406
402
410
MODAL INTENSITY DISTRIBUTION
REFRACTIVE INDEX
DISTANCE μM

FIG. 4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8
0
0
5
TIME NS
INJECTION CURRENT A
OUTPUT POWER W
CARRIER DENSITY 10^{18} CM^3
502
506
504
508
500

FIG. 5

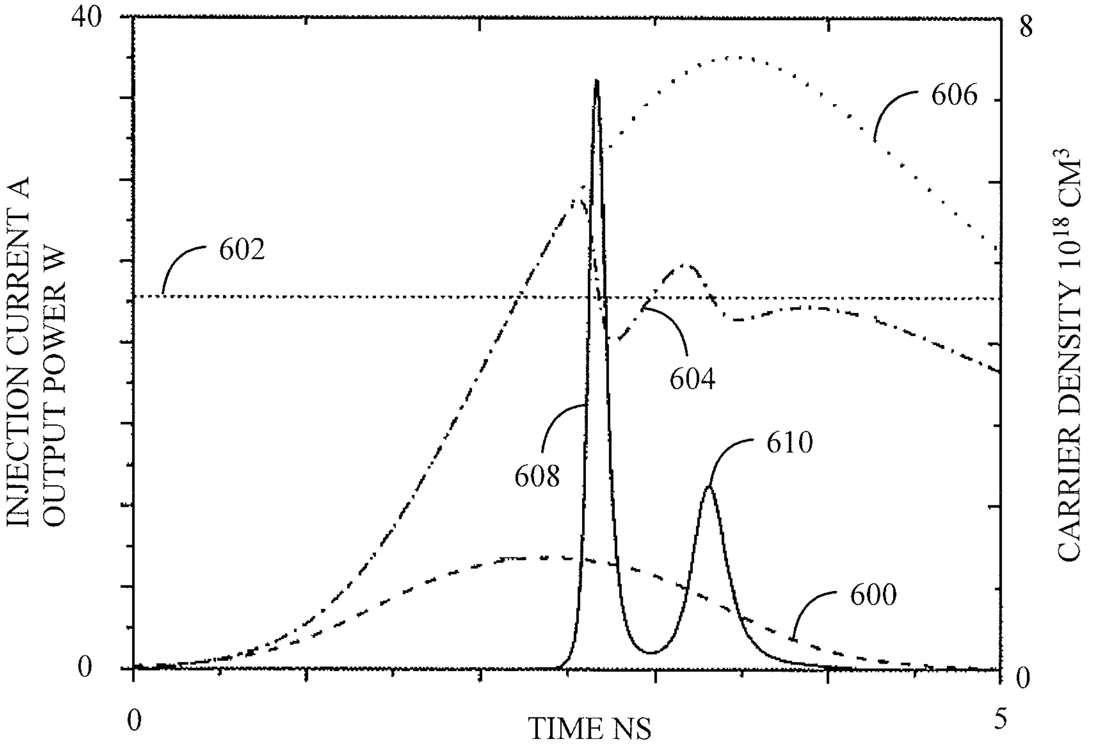
40
0
8
0
0
5
TIME NS
INJECTION CURRENT A
OUTPUT POWER W
CARRIER DENSITY 10^{18} CM^3
602
606
604
608
610
600

FIG. 6

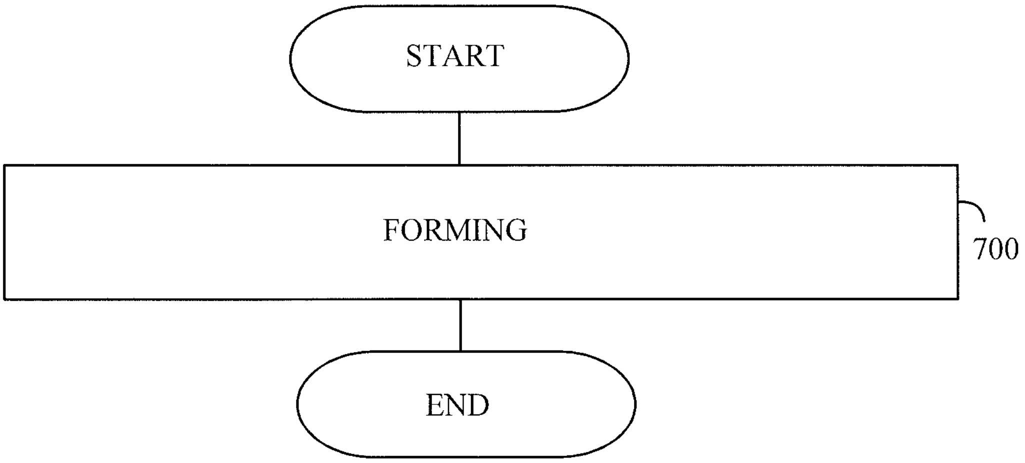

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.

PCT/FI2009/050438

A. CLASSIFICATION OF SUBJECT MATTER

See extra sheet

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: H01S

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

FI, SE, NO, DK

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

EPO-Internal, WPI, XPIEE, XPI3E, XPAIP, XPESP, XPIOP, INSPEC, COMPDX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 9116747 A1 (INST DE FIZICA ATOMICA) 31 October 1991 (31.10.1991), abstract; pp. 4-5;p. 9, l. 12;p. 18, l. 20; figs.	1, 2, 5-9, 12-14
X	US 6324199 B1 (CAPASSO FEDERICO et al.) 27 November 2001 (27.11.2001), whole document.	1, 5-8, 12-14
X	US 2007036190 A1 (ABELES JOSEPH H et al.) 15 February 2007 (15.02.2007), par. [0021]-[0065]; table I; fig. 5A.	1-3, 6, 8-10, 13
X	WO 9608062 A1 (PETRESCU PRAHOVA IULIAN BASARA et al.) 14 March 1996 (14.03.1996), abstract; p. 2, l. 14 – p. 3, l. 25.; p. 7; fig. 2.	1-3, 5-10, 12-14
A	VAINSHTEIN, S. N. et al., Deriving of single intensive picosecond optical pulses from a high-power gain-switched laser diode by spectral filtering. Journal of Applied Physics. 15 October 1998, Vol.84, No.8, pages 4109-4113, ISSN 0021-8979., whole document.	1-14

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
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"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search 28 August 2009 (28.08.2009)	Date of mailing of the international search report 14 September 2009 (14.09.2009)
Name and mailing address of the ISA/FI National Board of Patents and Registration of Finland P.O. Box 1160, FI-00101 HELSINKI, Finland Facsimile No. +358 9 6939 5328	Authorized officer Olli-Pekka Sievänen Telephone No. +358 9 6939 500

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/FI2009/050438

Patent document cited in search report	Publication date	Patent family members(s)	Publication date
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CLASSIFICATION OF SUBJECT MATTER

Int.Cl.
H01S 5/062 (2006.01)
H01S 5/042 (2006.01)
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