A method for producing an optical output includes the following steps: providing first and second electrical signals; providing a bipolar light-emitting transistor device that includes collector, base, and emitter regions; providing a collector electrode coupled with
(57) Abrégé(suite)/Abstract(continued):
the collector region and an emitter electrode coupled with the emitter region, and coupling electrical potentials with respect to the collector and emitter electrodes; providing an optical coupling in optical communication with the base region; providing first and second base electrodes coupled with the base region; and coupling the first and second electrical signals with the first and second base electrodes, respectively, to produce an optical output emitted from the base region and coupled into the optical coupling, the optical output being a function of the first and second electrical signals. Also disclosed in an improved pnp transistor laser and a technique for switching back and forth between a stimulated emission mode that produces output laser pulses and a spontaneous emission mode.
Title: SEMICONDUCTOR BIPOLAR LIGHT EMITTING AND LASER DEVICES AND METHODS

Abstract: A method for producing an optical output includes the following steps: providing first and second electrical signals; providing a bipolar light-emitting transistor device that includes collector, base, and emitter regions; providing a collector electrode coupled with the collector region and an emitter electrode coupled with the emitter region, and coupling electrical potentials with respect to the collector and emitter electrodes; providing an optical coupling in optical communication with the base region; providing first and second base electrodes coupled with the base region; and coupling the first and second electrical signals with the first and second base electrodes, respectively, to produce an optical output emitted from the base region and coupled into the optical coupling, the optical output being a function of the first and second electrical signals. Also disclosed in an improved pnp transistor laser and a technique for switching back and forth between a stimulated emission mode that produces output laser pulses and a spontaneous emission mode.
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SEMICONDUCTOR BIPOLAR LIGHT EMITTING AND LASER DEVICES AND METHODS

FIELD OF THE INVENTION

This invention relates to semiconductor light emitting and laser devices and methods, and also to a laser transistors and techniques for enhancing high speed optical signal generation, and also to devices and methods that include wave mixing modulation laser transistors and techniques, and also to PNP bipolar transistors, PNP bipolar light emitting transistors, and PNP bipolar transistor lasers.

BACKGROUND OF THE INVENTION

A part of the background hereof lies in the development of light emitters based on direct bandgap semiconductors such as III-V semiconductors. Such devices, including light emitting diodes and laser diodes, are in widespread commercial use.

Another part of the background hereof lies in the development of wide bandgap semiconductors to achieve high minority carrier injection efficiency in a device known as a heterojunction bipolar transistor (HBT), which was first proposed in 1948 (see e.g. U.S. Patent 2,569,376; see also H. Kroemer, “Theory Of A Wide-Gap Emitter For Transistors” Proceedings Of The IRE, 45, 1535-1544 (1957)). In recent years, these transistor devices are capable of operation at extremely high speeds. For example, in 2003, an InP HBT was demonstrated to exhibit operation at a speed above 500 GHz (see W. Hafez, J.W. Lai, and M. Feng, Elec Lett. 39, 1475 (Oct. 2003).

The art had contained an objective of light emission in a heterojunction bipolar transistor, and a theoretical striving for a laser transistor. However, for various reasons, an operational bipolar laser transistor was not reported before the
earliest priority Application hereof, and the achievement of same was one of the objectives hereof. Also, control of a laser transistor, to achieve advantageous high speed optical signals, is among the further objectives hereof.

It is also among the objects of the present invention to produce heterojunction bipolar transistor lasers and techniques that are capable of advantageous signal processing to obtain a variety of selected optical outputs, including wave mixing modulation laser transistors and techniques.

The first operational bipolar transistor lasers, on which we have reported, have been npn transistors (see, for example, M. Feng, N. Holonyak, Jr., B. Chu-Kung, G. Walter, and R. Chan, "Type-II GaAsSb/InP Heterojunction Bipolar Light-Emitting Transistor", Appl. Phys. Lett. 84, 4792 (2004)).

This is not surprising. In several respects, p-type material is recognized as being more difficult to work with than n-type material, and tends to be operationally inferior to corresponding n-type material with regard to carrier mobility and overall electrical efficiency. Accordingly, it is often considered desirable to favor the use of n-type semiconductor material in the fabrication of semiconductor devices such as III-V light emitting devices. However, even though the substrate and a fractional majority of the semiconductor volume in such devices may be n-type semiconductor or undoped semiconductor, a substantial amount of p-type material is generally considered necessary as a source of hole current in various semiconductor devices.

It is among the further objects of the present invention to provide improved pnp bipolar transistors, and especially pnp light emitting bipolar transistors, including pnp bipolar transistor lasers.
SUMMARY OF THE INVENTION

In our PCT International Publication Number WO 2005/020287, there is disclosed a direct bandgap heterojunction transistor that exhibits light emission from the base layer. Modulation of the base current produces modulated light emission. [As used herein, "light" means optical radiation that can be within or outside the visible range.] The referenced PCT Publication WO 2005/020287 also discloses three port operation of a light emitting HBT. Both spontaneous light emission and electrical signal output are modulated by a signal applied to the base of the HBT.

Another aspect of the referenced PCT Publication WO 2005/020287 involves employing stimulated emission to advantage in the base layer of a bipolar transistor (e.g. a bipolar junction transistor (BJT) or a heterojunction bipolar transistor (HBT), in order to enhance the speed of the transistor. Spontaneous emission recombination lifetime is a fundamental limitation of bipolar transistor speed. In an embodiment of the referenced PCT Publication WO 2005/020287, the base layer of a bipolar transistor is adapted to enhance stimulated emission (or stimulated recombination) to the detriment of spontaneous emission, thereby reducing recombination lifetime and increasing transistor speed. In a form of this embodiment, at least one layer exhibiting quantum size effects, preferably a quantum well or a layer of quantum dots, preferably undoped or lightly doped, is provided in the base layer of a bipolar transistor. At least a portion of the base layer containing the at least one layer exhibiting quantum size effects, is highly doped, and of a wider bandgap material than the at least one layer. The at least one quantum well, or layer of quantum dots, within the higher gap highly doped material, enhances stimulated recombination and reduces radiative recombination lifetime. A two-dimensional electron gas ("2-DEG") enhances carrier concentration in the quantum well or quantum dot layer, thereby improving mobility in the base region. Improvement in base resistance permits reduction in base thickness, with attendant reduction of base transport time. As described in the referenced PCT Publication WO 2005/020287, these advantages in speed are applicable in high speed bipolar transistors in which light emission is utilized, and/or in high speed
bipolar transistors in which light emission is not utilized. In light emitting bipolar transistor devices, for example heterojunction bipolar transistors of direct bandgap materials, the use of one or more layers exhibiting quantum size effects can also be advantageous in enhancing light emission and customizing the emission wavelength characteristics of the devices.

In a further embodiment disclosed in the referenced PCT Publication WO 2005/020287, a semiconductor laser is set forth, including: a heterojunction bipolar transistor structure comprising collector, base, and emitter of direct bandgap semiconductor materials; an optical resonant cavity enclosing at least a portion of the transistor structure; and means for coupling electrical signals with the collector, base, and emitter regions to cause laser emission from the device.

In another embodiment disclosed in the referenced PCT Publication WO 2005/020287, a plurality of spaced apart quantum size regions (e.g. quantum wells and/or quantum dots) having different thicknesses are provided in the base region of a bipolar transistor and are used to advantageously promote carrier transport unidirectionally through the base region. As an example, the base region can be provided with several spaced apart quantum size regions of different thicknesses, with the thicknesses of the quantum size regions being graded from thinnest near the collector to thinnest near the emitter. An injected electron is captured in a smaller well, tunnels into the next bigger well, and then the next bigger well, and so forth, until, at the biggest well closest to the collector, it tunnels to and relaxes to the lowest state of the biggest well and recombines. The arrangement of wells encourages carrier transport unidirectionally from emitter toward collector. Maximum recombination and light are derived from the biggest well as near as possible to the collector, which is an advantageous position, such as for optical cavity reasons. Carriers diffuse "downhill" in energy; i.e., toward the thicker wells. The asymmetry in well size provides improved directionality and speed of carrier transport. In a light emitting HBT, light emission and device speed are both enhanced.

In accordance with an embodiment of the present invention, a device and technique are set forth for high speed optical signal generation with an enhanced signal to noise ratio and control of "on" and "off" time durations utilizing the
stimulated emission process for the "on" state and spontaneous emission process for the "off" state. The operating point and excitation of the transistor laser are selected to obtain cycles that each have an "on" portion of stimulated emission (laser optical output, and electrical signal output) and an "off" portion of spontaneous emission (without sensible optical output, and electrical noise).

A method is set forth in accordance with an embodiment of the invention for producing controllable light pulses, including the following steps: providing a heterojunction bipolar transistor structure comprising collector, base, and emitter regions of semiconductor materials; providing an optical resonant cavity enclosing at least a portion of the transistor structure; and coupling electrical signals with respect to said collector, base, and emitter regions, to switch back and forth between a stimulated emission mode that produces output laser pulses and a spontaneous emission mode. In a preferred embodiment, the electrical signals include an AC excitation signal, and part of each excitation signal cycle is operative to produce stimulated emission, and another part of each excitation signal cycle is operative to produce spontaneous emission. In this embodiment, during said part of the cycle, the current in the base region exceeds the stimulated emission threshold of the device, and during said other part of the cycle, the current in the base region does not exceed said threshold. Also in this embodiment, the frequency of the excitation signal controls the frequency of the output laser pulses and the relative amplitude of the excitation signal controls the pulse width of the output laser pulses. In a form of this embodiment, the AC excitation signal is provided at a frequency of at least about 1 GHz, and the pulse width of the output laser pulses is controlled to be less than about 100 picoseconds.

In accordance with another embodiment of the present invention, a method is set forth for producing an optical output, comprising the following steps: providing first and second electrical signals; providing a bipolar light-emitting transistor device that includes collector, base, and emitter regions; providing a collector electrode coupled with said collector region and an emitter electrode coupled with said emitter region, and coupling electrical potentials with respect to said collector and emitter electrodes; providing an optical coupling in optical communication with said base region; providing first and second base electrodes
coupled with said base region; and coupling said first and second electrical signals with said first and second base electrodes, respectively, to produce an optical output emitted from said base region and coupled into the optical coupling, said optical output being a function of said first and second electrical signals. In one preferred embodiment of the invention, the step of providing a bipolar light-emitting transistor device comprises providing a laser transistor, and the optical output comprises a plurality of coupled laser beams. In a form of this embodiment, the first electrical signal has a frequency \( f_1 \), the second electrical signal has a frequency \( f_2 \), and said optical output includes a frequency component from the group consisting of \( f_1 + f_2 \), \( |f_1 - f_2| \), \( 2f_1 + f_2 \), \( 2f_2 + f_1 \), \( 2f_1 - f_2 \), and \( 2f_2 - f_1 \).

In another embodiment, the step of providing first and second electrical signals comprises providing first and second controllable oscillators for producing said first and second electrical signals.

In a further embodiment, the step of providing first and second electrical signals comprises providing a signal generator for producing said first and second electrical signals, and a phase shifter for producing a phase shift between said first and second electrical signals.

For some applications, it may be desirable that a transistor laser be a pnp HBT rather than an npn HBT, assuming this leads to lower base region resistive loss (which is driven by lateral base currents) and, in addition, assuming lower free carrier absorption (\( N_{\text{DONOR}} < N_{\text{ACCEPTOR}} \)) since the base is located largely in the high field active region. In such applications we prefer to put heavily doped p-type crystal outside of the base region and to some extent outside of the high field active region of the transistor laser. Accordingly, one of the features of a further aspect of the invention is to devise an improved HBT laser, and to minimize the amount of acceptor-doped crystal required in the p-type emitter and in the high field p-type collector, by making these regions relatively thin and contacting them via tunnel junctions (i.e., p+ region contacted by n+ region to minimize the total thickness of p-type emitter and collector). [The "+" notation conventionally means "heavily doped", and, for purposes hereof, is generally donor impurity concentration of at least about \( 10^{18}/\text{cm}^3 \) for n+, and acceptor impurity concentration of at least about \( 10^{19}/\text{cm}^3 \) for p+.] In accordance with a feature of this aspect of the
invention, a pnp HBT light emitter is made with just enough p-type crystal to render operative the emitter (hole injection) function and the carrier collector function. That is, the current of the device is carried, to the extent possible, in higher mobility n-type crystal and not lower mobility p-type crystal, thereby minimizing resistive loss. Tunneling in GaAs, at an n+/p+ junction, is well known (see, for example, N. Holonyak, Jr. and I.A. Lesk, Proc. IRE 48, 1405, 1960), and was once generally of interest for its negative resistance. Tunneling in GaAs can be enhanced with an InGaAs transition region (see, for example, T.A. Richard, E.I. Chen, A.R. Sugg, G.E. Hofler, and N. Holonyak, Jr., Appl. Phys. Lett. 63, 3613, 1993), and besides its negative resistance behavior, can be used in reverse bias as a form of "ohmic" contact. This allows, for example, the reversal of the doping sequence of an AlₓGa₁₋ₓAs-GaAs quantum well heterostructure laser (n → p to p → n) grown on an n-type GaAs substrate (see, for example, A.R. Sugg, E.I. Chen, T.A. Richard, S.A. Maranowski, and N. Holonyak, Jr., Appl. Phys. Lett. 62, 2510 (1993)). As described in the background portion of Holonyak et al. U.S. Patent 5,936,266, a tunnel contact junction can be used in a light emitting semiconductor diode as a hole source and makes possible lateral bias currents (electron current) to drive a quantum well heterostructure (QWH) laser diode without the compromise of the low mobility and large resistive voltage drop of lateral conduction in thin p-type layers. This is particularly valuable in QWH laser diodes employing upper and/or lower native oxide confining layers (see, for example, M. Dallesasse, N. Holonyak Jr., A.R. Sugg, T.A. Richard, and N. El Zein, Appl. Phys. Lett 57 2844, 1990; A.R. Sugg, E.I. Chen, T.A. Richard, N. Holonyak, Jr., and K.C. Hsieh, Appl. Phys. Lett. 62, 1259, 1993) that require lateral bias currents (see, for example, P.W. Evans, N. Holonyak, Jr., S.A. Maranowski, M.J. Ries, and E.I. Chen, Appl. Phys. Lett. 67, 3168, 1995), or in devices such as a vertical cavity surface emitting laser (VCSEL) where lateral hole currents have been employed (see, for example, D.L. Huffker, D.G. Deppe, and K. Kumar, Appl. Phys. Lett. 65, 97, 1994). The structure in the U.S. Patent 5,936,266 involved lateral current flow in laser diodes with hole conduction along a layer introducing a large device series resistance, because of the low hole mobility in GaAs, with increased threshold voltages and device heating. The solution to this drawback in the ‘266 Patent involved a tunnel contact
junction on the p side of an oxide confined QWH that was used to replace lateral hole excitation currents. The hole injection was supported by a lateral electron current, thus providing lower voltage drop and less series resistance. One of the objectives there, as here, was to minimize the amount of p-type material and, to the extent possible, employ only n-type layers (electron conduction) to carry the device current. However, the problems in the present situation have different aspects, since a bipolar transistor is involved. As will be seen, part of the solution involves use of a tunnel junction for conversion from electron current to hole current, and another part of the solution involves use of a tunnel junction, in opposing orientation, for conversion of hole current to electron current.

In accordance with another embodiment of the invention, there is provided a semiconductor light-emitting transistor device which comprises: a bipolar npn transistor structure having a p-type collector, an n-type base, and a p-type emitter; a first tunnel junction coupled with said collector, and a second tunnel junction coupled with said emitter; and a collector contact coupled with said first tunnel junction, an emitter contact coupled with said second tunnel junction, and a base contact coupled with said base; whereby, signals applied with respect to said collector, base, and emitter contacts causes light emission from said base by radiative recombination in said base. In a preferred form of this embodiment of the invention, the first tunnel junction comprises a layered n+/p+ region with the n+ layer of said n+/p+ region being coupled with said collector contact and the p+ layer of said n+/p+ region being coupled with said collector. Also, the second tunnel junction comprises a layered n+/p+ region with the n+ layer of said n+/p+ region being coupled with said emitter contact and the p+ layer of said n+/p+ region being coupled with said emitter.

A form of the described embodiment is a semiconductor laser device comprising the above-defined semiconductor light-emitting transistor device, further including an optical resonant cavity enclosing at least a portion of the base of said device. In one version of this form of the invention, at least a portion of said device is in layered form, and the optical resonant cavity is a lateral cavity with respect to the layer plane of said at least a portion of said device. In another version of this form of the invention, the optical resonant cavity is a vertical cavity
with respect to the layer plane of said at least a portion of said device. Also in a preferred embodiment, the base of said device comprises a heavily doped n+ region, and there is further provided a region in said base exhibiting quantum size effects, such as one or more quantum wells and/or quantum dot layers.

In accordance with another related embodiment of the invention, a method is set forth for producing light modulated with an input electrical signal, including the following steps: providing a bipolar transistor device that includes a p-type collector, an n-type base, and a p-type emitter; providing a first tunnel junction coupled with said collector, and a second tunnel junction coupled with said emitter; providing a collector contact coupled with said first tunnel junction, and providing an emitter contact coupled with said second tunnel junction, and providing a base contact coupled with said base; applying electrical signals with respect to said collector, base, and emitter contacts to cause light emission by radiative recombination in the base region; and controlling the base current of said transistor device with said input electrical signal to modulate the light emission from said transistor device.

The pnp transistor laser can have a number of advantages as compared to the npn transistor laser, as follows: (1) Lower base doping, with resultant reduction in free carrier absorption, lower lasing threshold, and reduced self-heating in the base region, as well as improved QW recombination spectra. (2) Lower base sheet resistance due to superior electron mobility, with accordant improvement in upper base current injection limit, higher power operation, reduced resistive heating in the base region, and also improved base current distribution under the emitter, resulting in lower lasing threshold and reduced edge heating. (3) Lower contact resistance, with resulting reduction in heating effect.

On top of the listed advantages, this form of the invention, employing the described tunnel junctions in the pnp transistor laser, can have a number of further advantages, as follows: (1) Reduced contact resistance to emitter and collector contact layers, resulting in reduced heating effect and reduced capacitive effect. (2) Lower collector sheet resistance, resulting in reduced heating effect and higher upper power (collector current x V_{CE}) limit for collector current. (3) Lower series resistance through the emitter cladding layer, and accordant reduction of heating
effect. (4) Lower free carrier absorption in the upper and lower cladding region (by minimization of highly doped P-region), resulting in reduced free carrier absorption, and accordant lower lasing threshold and reduced heating effect. It is recognized that the pnp HBT laser may not operate as at high a speed as a super high speed npn HBT, but it can still be an extremely high speed transistor laser with relatively lower current threshold and relatively higher collector voltage breakdown.

Further features and advantages of the invention will become more readily apparent from the following detailed description when taken in conjunction with the accompanying drawings.
BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a simplified cross-sectional diagram, not to scale, of a light emitting transistor as described in a referenced published PCT Application.

Figure 2 shows, on the left, a diagram, not to scale, of the epitaxial layers of a crystal used for making a heterojunction bipolar light-emitting transistor (HBLET) in accordance with an embodiment of the invention and which can be used in practicing embodiments of the method of the invention, and, on the right, a corresponding band diagram.

Figure 3 shows, on the left, a processed, metallized, and cleaved HBLET laser (top view) as made using the crystal of Figure 2 and, on the right, an image of the operating device obtained with a video CCD detector.

Figure 4 shows the transistor I-V curves of another HBLET laser with ~ 260 μm spacing between the Fabry-Perot facets.

Figure 5 shows, in quasi-continuous operation (88% duty cycle at 60 Hz), the recombination radiation spectra of the HBLET device of Figure 3, but with slightly increased voltage bias $V_{CE}$ to increase the reverse bias on the base-collector junction.

Figure 6 shows the transistor $I_C$ versus $V_{CE}$ family of curves (at 213 K) of a 450 μm HBLET of another device in accordance with an embodiment of the invention and which can be used in practicing embodiments of the method of the invention.

Figure 7 shows, in the curves (a) and (b), respectively, the small signal current gain $\beta_{ac} = \Delta I_C/\Delta I_B$ and current gain $\beta_{dc} = I_C/I_B$ for $V_{CE} = 0$ for the device whose $I_C$ curves are shown in Figure 6.

Figure 8 shows (at 213 K) the laser operation (curve (a)) and spontaneous spectrum (curve (b)) power spectra of the transistor laser biased at $V_{CE} = 2$ V and operating at 3 GHz.

Figure 9 shows a picture of the transistor laser in operation at 3 GHz, captured using a CCD camera.

Figure 10 shows, in traces (a), (b) and (c), respectively, the input signal modulated at 3 GHz, and the corresponding electrical and optical outputs.
Figure 11 shows the output collector I-V characteristics of an HBLET. For the base current below laser threshold $I_{th} = 0.744\text{mA}$, the optical recombination process yields spontaneous emission (low optical output). For base current above laser threshold the optical recombination process is stimulated (higher optical output power).

Figure 12 shows a Gummel plot of base current and collector current with $V_{ce} = V_{be}$ and $V_{bc} = 0V$. The current gain beta increases (spontaneous emission), and the beta decreases when laser operation of the HBLET starts, since the recombination process for stimulated emission become "faster".

Figures 13(a), 13(b), 13(c), and 13(d) show, respectively, the input voltage, output voltage, optical output, and optical power spectrum for a laser transistor device operated in a stimulated emission mode.

Figures 14(a), 14(b), and 14(c), show, respectively, the input voltage, optical output, and optical power spectrum for a laser transistor device operated in a spontaneous emission mode.

Figures 15(a), 15(b), 15(c), and 15(d) show, respectively, the input voltage, output voltage, optical output, and optical power spectrum for a laser transistor device operated in a near-threshold mode.

Figure 16 is a schematic diagram of an example of a circuit that can be used to operate a light emitting transistor in accordance with an embodiment of the invention.

Figure 17 shows output collector I-V characteristics of an HBLET, and signals that result when operated at different operating points.

Figure 18 shows the electrical output for operation at each of the different operating points.

Figure 19 shows the optical output for operation at each of the different operating points.

Figure 20 is a simplified schematic diagram of a three port device as disclosed in the referenced PCT Publication WO 2005/020287.

Figure 21 illustrates reflectors used in a bipolar transistor laser device as disclosed in the referenced PCT Publication WO 2005/020287.
Figure 22 shows a portion of a device disclosed in the referenced PCT Publication WO 2005/020287, employing one or more quantum wells.

Figure 23 shows a portion of a device disclosed in the referenced PCT Publication WO 2005/020287, employing one or more regions of quantum dots.

Figure 24 shows a portion of a device employing a quantum well and, spaced therefrom, a layer of quantum dots.

Figure 25 is a simplified cross-sectional diagram, not to scale, of a vertical cavity surface emitting laser as described in the referenced PCT Publication WO 2005/020287.

Figure 26 is a simplified cross-sectional diagram, not to scale, of another vertical cavity surface emitting laser as described in the referenced PCT Publication WO 2005/020287.

Figure 27 is a diagram, partially in cross section and partially in schematic form, of a device and system in accordance with an embodiment of the invention, and which can be used in practicing an embodiment of the method of the invention.

Figure 28 is a diagram, partially in cross section and partially in schematic form, of a device and system in accordance with another embodiment of the invention, and which can be used in practicing another embodiment of the method of the invention.

Figure 29 is a diagram, partially in cross section and partially in schematic form, of a device and system in accordance with a further embodiment of the invention, and which can be used in practicing a further embodiment of the method of the invention.

Figure 30 is a diagram, partially in cross section and partially in schematic form, of a device and system in accordance with a still further embodiment of the invention, and which can be used in practicing a still further embodiment of the method of the invention.

Figure 31 shows another embodiment of the invention.

Figure 32 is a simplified diagram, not to scale, of the layer structure of a pnp HBT laser in accordance with an embodiment of the invention and which can be used in practicing an embodiment of the method of the invention.
Figure 33 is a simplified diagram, not to scale, of the layer structure of a pnp HBT laser in accordance with another embodiment of the invention and which can be used in practicing an embodiment of the method of the invention.

Figure 34 is a diagram, not to scale, of the detailed layer structure of the Figure 31 embodiment.

Figure 35 is a diagram that illustrates the carrier flow pattern for an embodiment of the invention.
Figure 1 illustrates a device as set forth in referenced PCT Publication WO 2005/020287. A substrate 105 has the following layers disposed thereon: subcollector 110, collector 130, base 140, emitter 150, and cap layer 160. Also shown are collector metallization (or electrode) 115, base metallization 145, and emitter metallization 165. Collector lead 117, base lead 147, and emitter lead 167 are also shown. As described in the referenced copending Application, the collector layer 130 comprises 3000 Angstrom thick n-type GaAs, $n = 2 \times 10^{16}$ cm$^{-3}$, the base layer 140 comprises 600 Angstrom thick p+ carbon-doped compositionally graded InGaAs (1.4% In), $p = 4.5 \times 10^{18}$ cm$^{-3}$, the emitter layer 150 comprises 800 Angstrom thick n-type InGaP, $n=5 \times 10^{17}$ cm$^{-3}$, and the cap layer comprises 1000 Angstrom thick n+ InGaAs, $n = 3 \times 10^{18}$ cm$^{-3}$.

As described in the referenced PCT Publication WO 2005/020287, for conventional PN junction diode operation, the recombination process is based on both an electron injected from the n-side and a hole injected from the p-side, which in a bimolecular recombination process can be limited in speed. In the case of HBT light emission, the base "hole" concentration is so high that when an electron is injected into the base, it recombines (bimolecular) rapidly. The base current merely re-supplies holes via relaxation to neutralize charge imbalance. For a heterojunction bipolar transistor (HBT), the base current can be classified into seven components, namely: (1) hole injection into the emitter region ($I_{BE}$); (2) surface recombination current in the exposed extrinsic base region ($I_{Bsurf}$); (3) base ohmic contact recombination current ($I_{Bcont}$); (4) space charge recombination current ($I_{Bscr}$); (5) bulk base non-radiative recombination current due to the Hall-Shockley-Reed process (HSR) ($I_{BHSR}$); (6) bulk base Auger recombination current ($I_{BAug}$); and (7) bulk base radiative recombination current ($I_{Brad}$). For a relatively efficient HBT with ledge passivation on any exposed base region, the surface recombination current can be reduced significantly. Hence, the base current and recombination lifetime can be approximated as primarily bulk HSR recombination, the Auger process, and radiative recombination. The base current expressed in the following equation (1) is then related to excess minority carriers, $\Delta n$, in the
neutral base region, the emitter area, \( A_E \), the charge, \( q \), and the base recombination lifetime, \( \tau_n \) as

\[
i_B = i_{BHR} + i_{BAUG} + i_{BRad} = q A_E \Delta n / \tau_n
\]  \( \text{(1)} \)

The overall base recombination lifetime, \( \tau_n \), is related to the separate recombination components of Hall-Shockley-Read, \( \tau_{HSR} \), Auger, \( \tau_{AUG} \), and radiative recombination, \( \tau_{rad} \), as

\[
\tau_n = \left( 1 / \tau_{HSR} + 1 / \tau_{AUG} + 1 / \tau_{rad} \right)^{-1}
\]  \( \text{(2)} \)

As further described in the referenced PCT Publication WO 2005/020287, the light emission intensity \( \Delta I \) in the base is proportional to \( i_{BRad} \) and is related to the minority carrier electron with the majority hole over the intrinsic carrier concentration, \( (np-n_i^2) \), in the neutral base region and the rate of radiative recombination process, \( B \), set forth in Equation (3) below, where the hole concentration can be approximated as equal to base dopant concentration, \( N_B \).

The radiative base current expressed in equation (3) is then related to excess minority carriers, \( \Delta n \), in the neutral base region, and the base recombination lifetime, \( \tau_{rad} \) as

\[
i_{BRad} = q A_E B (np-n_i^2) = q A_E B n p = q A_E \Delta n (BN_B) = q A_E \Delta n / \tau_{rad}
\]  \( \text{(3)} \)

For a high speed HBT, it is easy to predict that the base recombination lifetime can be less than half of the total response delay time. Hence, the optical recombination process in the base should be at least two times faster than the speed of the HBT. In other words, HBT speed, which can be extremely fast, is limiting.

In a first illustrated embodiment, a device and data are set forth showing laser operation of an InGaP-GaAs-InGaAs heterojunction bipolar light-emitting transistor (HBLET) with AlGaAs confining layers and an InGaAs recombination quantum well incorporated in the p-type base region. The epitaxial layers of the crystal used for the HBLET laser are shown schematically in Figure 2, with a GaAs substrate 210, a 4000 Å n-type heavily doped GaAs buffer layer 215, followed by a 600 Å n-type Al\(_{0.40}\)Ga\(_{0.60}\)As layer 220, a 3500 Å n-type Al\(_{0.96}\)Ga\(_{0.04}\)As layer 222, and a 400 Å n-type Al\(_{0.40}\)Ga\(_{0.60}\)As layer 224 forming the bottom cladding layers. These
layers are followed by a 400 Å n-type sub-collector layer 230, then a 200 Å In$_{0.49}$Ga$_{0.51}$P etch stop layer (not shown), a 650 Å undoped GaAs collector layer 240, and a 940 Å p-type GaAs base layer 250 (the active layer), which includes also (in the base region) a 120 Å InGaAs QW (designed for $\lambda \approx$ 980 nm). The epitaxial HBLET laser structure was completed with the growth of the upper cladding layers, which included a 1200 Å n-type In$_{0.49}$Ga$_{0.51}$P wide-gap emitter layer 260, a 300 Å n-type Al$_{0.70}$Ga$_{0.30}$As oxidation buffer layer 270, a 3500 Å n-type Al$_{0.90}$Ga$_{0.10}$As oxidizable layer 275 (see J.M. Dallesasse, N. Holonyak, Jr., A.R. Sugg, T.A. Richard, and N. El-Zein, Appl. Phys. Lett. 57, 2844 (1990)), and a 1000 Å n-type Al$_{0.40}$Ga$_{0.60}$As layer 280. Finally, the HBLET laser structure was capped with a 1000 Å heavily doped n-type GaAs contact layer 290.

The HBLET laser fabrication was performed by first patterning 6 μm protective SiN$_4$ stripes on the crystal. The top n-type Al$_{0.98}$Ga$_{0.02}$As oxidizable layer was then exposed by wet etching (1:8:160 H$_2$O$_2$:H$_2$SO$_4$:H$_2$O) to form a ~6 μm emitter mesa. Next, a wide 150 μm protective photoresist (PR) stripe was placed over the emitter mesa and the unprotected Al$_{0.98}$Ga$_{0.02}$As layer was completely removed (1:4:80 H$_2$O$_2$:H$_2$SO$_4$:H$_2$O), revealing the In$_{0.49}$Ga$_{0.51}$P wide-gap emitter layer. The protective PR stripe was then removed and the sample was oxidized for 7.5 min at 425 °C in a furnace supplied with N$_2$+H$_2$O, resulting in a ~1.0 μm lateral oxidation which formed ~4 μm oxide-defined apertures in the 6 μm emitter mesa (see, again, J.M. Dallesasse, N. Holonyak, Jr., A.R. Sugg, T.A. Richard, and N. El-Zein, supra (1990); S.A. Maranowski, A.R. Sugg, E.I. Chen, and N. Holonyak, Jr., Appl. Phys. Lett. 63, 1660 (1993)). The samples were annealed (in N$_2$) at 430 °C for 7 minutes to reactivate p-dopants before the protective SiN$_4$ was removed by plasma (CF$_4$) etching. A 100 μm PR window was formed over the emitter mesa and oxide layer, and Au-Ge/Au was deposited over the sample to form metal contact. After lift-off of the photoresist (PR) to remove excess metal, the In$_{0.49}$Ga$_{0.51}$P layer was removed using a wet etch (4:1 HCl: H$_2$O), exposing the p-type GaAs base layer. An 80 μm wide PR window was then patterned ~15 μm away from the emitter mesa edge, and Ti-Pt-Au was evaporated for contact to the base. Another lift-off process was then performed to remove excess base contact metal. A 150 μm PR window was then patterned ~6 μm away from the base.
contact. The GaAs base and collector layers were removed using a selective etch (4:1 \(\text{C}_6\text{H}_8\text{O}_7:\text{H}_2\text{O}_2\)), and the \(\text{In}_{0.49}\text{Ga}_{0.51}\text{P}\) etch-stop layer was removed by a wet etch (16:15 HCl: H\(_2\)O), exposing the heavily doped n-type GaAs sub-collector layer. Au-Ge/Au metal alloy was evaporated over the sample for contact to the exposed sub-collector layer, and another lift-off process was performed to remove excess metal. The sample was then lapped to a thickness of \(~75\ \mu m\) and the contacts annealed. The HBLET samples were cleaved normal to the emitter stripes to form Fabry-Perot facets, and the substrate side of the crystal was alloyed onto Cu heat sinks coated with In.

A processed, metallized, and cleaved HBLET laser (top view) is shown on the left in Figure 3. The contact probes on the emitter (E), base (B), and collector (C) are shown schematically resembling the actual probes (E\(_{\text{PRB}}\), B\(_{\text{PRB}}\), and C\(_{\text{PRB}}\)) on the operating device at the right. The image on the right was obtained with a video CCD detector and shows \((h\nu)\) the device laser beam (photons) scattered from a Cu platform located slightly lower than the laser crystal, which, as shown, has a \(~200\ \mu m\) spacing between the cleaved Fabry-Perot facets. Current and bias voltage (common emitter operation) were provided using a Tektronix Model 370 high resolution curve tracer connected to the HBLET by the three probes labeled E\(_{\text{PRB}}\), B\(_{\text{PRB}}\), and C\(_{\text{PRB}}\) in Figure 3. The HBLET laser was operated \(~200\) K in a dry \(\text{N}_2\) environment.

The transistor I-V curves of another HBLET laser with \(~260\ \mu m\) spacing between the Fabry-Perot facets are shown in Figure 4. As the base current, \(I_b\), is increased in 2 mA intervals from 0 to 8 mA, the usual increase of differential current gain is observed, \(\beta = \Delta I_o/\Delta I_b\), in this case from \(~2\) at lower current to 6.5 at higher current. Light versus \(V_{CE}\) measurements (\(I_b\) constant, data not shown) indicate that radiative recombination improves as \(V_{CE}\) increases and then decreases at the onset of reverse breakdown. Near \(I_b = 8\) mA, and as \(V_{CE}\) is increased, however, stimulated recombination (stimulated emission) becomes significant, and the HBLET operates both as a laser and a transistor but with a distinct decrease in the current gain \(\beta\). Beyond threshold, \(I_b\) equal to or greater than \(I_{th} \sim 8\) mA, the differential gain \(\beta\) decreases from 6.5 to a nearly constant value of 2.5 \((\alpha = \beta/(\beta+1) = I_o/I_e = 0.71)\). Since \(\beta\) can be approximated as the simple
ratio \( \tau_b/\tau_1 \) (see B.G. Streetman and S. Banerjee, Solid State Electronic Devices, 5th ed. (Pearson, New Jersey, 2004), p. 328), where \( \tau_1 \) is the average (carrier) base transit time (which is almost the same below and above threshold) and \( \tau_n \) is the average electron lifetime in the base, the electron lifetime is reduced by a factor of 2.6 because of the stimulated recombination of the carriers collected in the 120-Å QW. The QW operates as a unique pseudo-collector (see E.A. Rezek, H. Shichijo, B.A. Vojak, and N. Holonyak, Jr., Appl. Phys. Lett. 31, 534 (1977)), and can be adjusted to govern the base recombination and thus both the optical output and transistor gain (\( \beta \)). It can be noted for comparison that at room temperature there was observed (data not shown) a differential current gain \( \beta \) of 10 at \( I_b = 2 \) mA and 30 at 8 mA (or current transfer ratio, \( \alpha = I_d/I_e \) of 0.91 and 0.96).

Figure 5 shows, in quasi-continuous operation (88% duty cycle at 60 Hz), the recombination radiation spectra of the HBLET device of Figure 3, but with slightly increased voltage bias \( V_{CE} \) to increase the reverse bias on the base-collector junction. At (a) \( I_b = 6 \) mA, the HBLET recombination radiation exhibits a peak wavelength of 954 nm and a spectral width of \( \sim 280 \) Å. At (b) \( I_b = 8 \) mA, the onset of stimulated emission can be seen with distinct spectral narrowing and mode development. At (c) \( I_b = 10 \) mA the laser modes are fully developed (\( \lambda = 958 \) nm), clearly indicating transistor laser operation, which is evident also in Figure 3. It can be noted that the 200 μm long HBLET laser of Figure 3 (right side) was operated with pulsed base current (1% duty cycle at 1 MHz) to prevent saturation of the Si-CCD viewing camera.

The described results demonstrate that an HBLET, suitably modified with a resonator cavity and a recombination QW (or QWs) in the p-type base (a pseudo-collector, a second collector), can be operated simultaneously as a laser and transistor with gain \( \beta = \Delta I_d/\Delta I_b > 1 \). At laser threshold the transistor gain decreases sharply, but still supports three-port operation (electrical input, electrical output, and optical output).

In the description of the foregoing embodiment, it is shown that a heterojunction bipolar light emitting transistor (HBLET) having certain features, can support stimulated recombination and laser operation. In the following further embodiment, a three-port transistor laser, having certain features, exhibits microwave operation
and optical modulation. In this embodiment, the epitaxial layers of the crystal used for the HBLET laser include of a 100 Å n-type heavily doped GaAs buffer layer, followed by a 630 Å n-type Al$_{0.40}$Ga$_{0.60}$As layer, a 4000 Å n-type Al$_{0.98}$Ga$_{0.02}$As layer, and a 250 Å n-type Al$_{0.40}$Ga$_{0.60}$As layer forming the bottom cladding layers. These layers are followed by a 300 Å n-type sub-collector layer, then a 150 Å In$_{0.49}$Ga$_{0.51}$P etch stop layer, a 600 Å undoped GaAs collector layer, and a 850 Å p-type GaAs base layer, which includes also (in the base region) a 120 Å InGaAs QW (designed for $\lambda \approx 980$ nm). The epitaxial HBLET laser structure is completed with the growth of the upper cladding layers, which include a 600 Å n-type In$_{0.49}$Ga$_{0.51}$P wide-gap emitter layer, a 50 Å n-type GaAs buffer layer, a 200 Å n-type Al$_{0.35}$Ga$_{0.65}$As oxidation buffer layer, a 200 Å n-type Al$_{0.80}$Ga$_{0.20}$As oxidation buffer layer, a 4000 Å n-type Al$_{0.98}$Ga$_{0.02}$As oxidizable layer, a 300 Å n-type Al$_{0.80}$Ga$_{0.20}$As layer, and a 500 Å n-type Al$_{0.35}$Ga$_{0.65}$As layer. Finally, the HBLET laser structure is capped with a 1000 Å heavily doped n-type GaAs contact layer. The HBLET laser fabrication was performed by first patterning 8 μm protective SiN$_4$ stripes on the crystal. The top n-type Al$_{0.98}$Ga$_{0.02}$As oxidizable layer was then exposed by wet etching (1:8:160 H$_2$O$_2$:H$_2$SO$_4$:H$_2$O) to form a ~ 6 μm emitter mesa. Next, 10 μm and 50 μm (40 μm apart) photoresist (PR) windows were formed with the emitter mesa placed between the two windows and ~ 5 μm away from the 10 μm window. The unprotected Al$_{0.98}$Ga$_{0.02}$As layer was then completely removed (1:4:80 H$_2$O$_2$:H$_2$SO$_4$:H$_2$O), revealing the In$_{0.49}$Ga$_{0.51}$P wide-gap emitter layer. The protective PR stripe was dissolved and the sample was oxidized for 6.5 min at 425°C in a furnace supplied with N$_2$+H$_2$O, resulting in ~ 1.0 μm lateral oxidation which forms ~ 4 μm oxide-defined apertures in the 6 μm emitter mesa. (Again, see J.M. Dallesasse, N. Holonyak, Jr., A.R. Sugg, T.A. Richard, and N. El-Zein, Appl. Phys. Lett. 57, 2844 (1990); S.A. Maranowski, A.R. Sugg, E.I. Chen, and N. Holonyak, Jr., Appl. Phys. Lett. 63, 1660 (1993)). The samples were annealed (in N$_2$) at 430 °C for 6.5 minutes to reactivate p-dopants before the protective SiN$_4$ is removed by plasma (CF$_4$) etching. The remaining InGaP emitter was selectively etched using HCl. The base-collector contact layers were then exposed by a selective wet etch (4:1 C$_6$H$_5$O$_7$ : H$_2$O$_2$) for GaAs and InGaAs, and HCl for In$_{0.49}$Ga$_{0.51}$P. Then, a 50 μm PR window was formed over the 10 μm base contact.
window and the oxidized Al$_{0.69}$Ga$_{0.31}$As layer. A 1 μm thick Pd-Pt-Au p-type ohmic contact was deposited on top of the partially exposed base layer to form the base metal contact (followed by a lift-off process). Next, 30 μm and 50 μm (5 μm apart) PR windows were opened for the emitter and collector metal contact deposition, and 1 μm thick n-type contact AuGe-Ni-Au metal alloy was deposited on the crystal and another lift-off process was performed to remove excess metal. The sample was then lapped to a thickness of ~100 μm and annealed. The HBLET samples were cleaved normal to the emitter stripes to form Fabry-Perot facets, and the substrate side of the crystal was alloyed onto Cu heat sinks coated with indium.

The transistor $I_C$ versus $V_{CE}$ family of curves (at 213 K) of a 450 μm HBLET of this embodiment is shown in Figure 6. As the base current $I_B$ is increased in 2.5 mA intervals from 0 to 15 mA, the current gain ($\beta_{dc} = I_C/I_B$) increases to ~ 5.65 for $I_B \leq I_{th}$ and then decreases to ~ 4.5 for $I_B \geq I_{th}$. At $I_B = 7.5$ mA one observes in Figure 6 a negative slope in the differential or small signal $\beta$ ($\beta_{ac} = \Delta I_C/\Delta I_B$) associated with a transistor in laser operation, as described in conjunction with the previous embodiment. The transistor’s $V_{BE}$ curve is superimposed on the family of $I_C$ versus $V_{CE}$ curves to indicate the zero base-collector bias point, the boundary $V_{CB} = 0$. From Figure 6 and by observing the gain characteristic, it can be seen that the transistor operates as a laser over a wide range of $V_{CE}$ (beyond $V_{CB} = 0$). Light versus base current measurements (data not shown) indicate small variation in laser light intensity when the transistor operates in the saturation mode (constant $I_C$), and decreases at high reverse bias and the onset of heating.

A novel technique is used for determining the threshold current of a transistor laser that is based on the electrical gain of the transistor. This eliminates the need to have an additional external feedback system (photodetector) to verify that the device is operating as a laser. The small signal current gain $\beta_{ac} = \Delta I_C/\Delta I_B$ and current gain $\beta_{dc} = I_C/I_B$ for $V_{CB} = 0$ are shown by curves (a) and (b) of Figure 7. From curve (a) it can be observed that the small signal gain increases as $I_B$ increases and decreases sharply at the onset of stimulated emission, or for amplified spontaneous emission ($I_B = 6.7$ mA, $\beta_{ac}=8.6$). The peak of curve (b) in Figure 7 can be defined as the threshold current of the transistor laser ($I_B = I_{th} = 7.4$ mA). The transistor laser operation is fully developed when $\beta_{ac}$ reaches a minimum
\( \beta_{ae} = 3.7 \) at \( I_B \approx 7.9 \text{ mA} \). This method of threshold current measurement is verified by comparison with standard light versus intensity (L-I) measurements (data not shown) and from visual observation of the laser diffraction pattern using an infrared CCD camera. It is consistent also with spectral narrowing.

Figure 8 shows (at 213 K) the laser operation (curve (a)) and spontaneous spectrum (curve (b)) of the transistor laser of the present embodiment biased at \( V_{CE} = 2 \text{ V} \) and operating at 3 GHz. The input voltage waveform is generated using a clock signal from an HP70841A pattern generator which has a maximum clock signal of 3 GHz. The output measurements were made using an HP70951B optical spectrum analyzer. A maximum power level of -63.4 dBm was measured at \( \lambda = 966.5 \text{ nm} \) for the spontaneous emission, and for laser operation a power output of -21.44 dBm (\( \lambda = 964.4 \text{ nm} \)). The small output power of the transistor laser was attributed to weak fiber coupling. Additional free space measurements have yielded powers at least 8 times greater. A picture of the transistor laser in operation at 3 GHz, captured using a CCD camera, is shown in Figure 9. The light emission from the front Fabry-Perot facet was coupled (upward in Figure 9) into the optical fiber, which was connected directly into the input of the optical spectrum analyzer.

A signal generator, a wideband detector, a power meter and a digital oscilloscope were used for the three-port (electrical input, electrical output and optical output) direct modulation characterization of the transistor laser. A cold station equipped with a pair of 40 GHz ground-signal microwave probes was used to enable measurements at 213 K. The HBLET, with \( \sim 450 \mu\text{m} \) spacing between the Fabry-Perot facets, was biased in the normal operating mode (\( V_{CE} = 2 \text{ V} \) and \( I_B = 9 \text{ mA} \)), and a small signal sinusoidal voltage waveform with a peak-to-peak amplitude of 0.75 V was supplied to the base (input port) of the device. The input voltage waveform was generated using a clock signal from the HP70841A pattern generator (maximum clock signal of 3 GHz), and the electrical output collector-emitter voltage waveform was measured using a 20 GHz digital sampling oscilloscope. The complementary output of the input waveform clock signal was measured at a second separate channel of the oscilloscope. The output of the transistor laser was coupled into a multimode fiber probe with a core diameter of 25 \( \mu\text{m} \). The laser signal was fed into a high-speed (10 Gb/s) wideband (400 to
1700 nm) InGaAs detector. The detector output voltage, base input voltage, and collector output voltage were all displayed simultaneously on a four channel sampling oscilloscope. The input signal modulated at 3 GHz (top trace) and the corresponding electrical and optical outputs are shown in Figures 10 (a), (b) and (c), respectively. When the 3 GHz base current is held (decreased) below the threshold current, the optical output waveform was not observed, making evident, in contrast, that stimulated emission defines a much stronger laser output signal.

In accordance with an embodiment of the invention, a device and technique are set forth for high speed optical signal generation with an enhanced signal to noise ratio and control of “on” and “off” time durations utilizing the stimulated emission process for the “on” state and spontaneous emission process for the “off” state. The operating point and excitation of the transistor laser are selected to obtain cycles that each have an “on” portion of stimulated emission (laser optical output, and electrical signal output) and an “off” portion of spontaneous emission (without optical output, and electrical noise).

The transistor I-V curves of an HBLET laser with ~ 450 μm spacing between the Fabry-Perot facets are shown in Figure 11. At a base current I_b = 0.744 mA, the HBLET reaches laser threshold and changes transistor gain, \( \beta = \frac{dI_L}{dI_b} \), from \( \beta = 5.5 \) to 4.5 or \( \alpha = \beta/(\beta+1) = 0.85 \rightarrow 0.81 \). As above noted, an HBLET transistor laser has an important feature in the I-V curves in the transition from spontaneous emission to stimulated emission. Figure 12 shows a Gummel plot of base current and collector current with Vce = Vbe and Vbc = 0V. The current gain beta increases (spontaneous emission), and the beta decreases when laser operation of the HBLET starts, since the recombination process for stimulated emission become “faster”.

Experiments were conducted on the transistor laser in the common emitter configuration with 3 GHz modulation of the electrical input (controllable in frequency and amplitude) at the base terminal of the device.

A mode of operation termed a stimulated emission mode had, for example, the following initial operating parameters: \( V_{be} = 1.67 \) V, \( V_{ce} = 2 \) V, \( I_b = 16 \) mA and \( I_c = 69.2 \) mA. As expected, in the stimulated emission mode (i.e., with the input consistently at a level above the threshold for stimulated emission), the electrical
input and output, and the optical output as shown in graphs 13(a), 13(b), and 13(c), respectively, of Figure 11, are similar to the corresponding graphs 10(a), 10(b) and 10(c) of Figure 10 for a similar device, and the graph 13(d) of the laser power spectrum is similar to the corresponding graph of Figure 8 for the similar device.

A mode of operation termed a spontaneous emission mode had, for example, the following initial operating parameters: $V_{be} = 1.47$ V, $V_{ce} = 2$ V, $I_b = 5$ mA, and $I_c = 19.84$ mA. The graphs of Figure 14 show results for the spontaneous emission mode (i.e., with the input consistently at a level below the threshold for stimulated emission), the graph 14(a) showing the sinusoidal electrical input, the graph 14(b) showing the optical signal output, which is seen to be background noise characteristic of spontaneous emission, and the graph 14(c) showing the optical output power spectrum of the spontaneous emission mode.

A mode of operation termed a near-threshold mode had, for example, the following initial operating parameters: $V_{be} = 1.57$ V, $V_{ce} = 2$ V, $I_b = 10$ mA, and $I_c = 46.2$ mA. The graphs of Figure 15 show results for the near-threshold mode (i.e., with each cycle of the sinusoidal input signal having an “on” portion during which the base current exceeds the threshold for stimulated emission, and an “off” portion during which the base current is below the threshold for stimulated emission). The graphs 15(a) and 15(b) again show, respectively, the electrical input and output signals. The graph 15(c) shows the optical output, which is seen to have a stimulated emission laser pulse (during the part of the cycle when the base threshold current is exceeded) and spontaneous emission (during the part of the cycle when the base threshold current is not exceeded). In this case, for the 3 GHz input signal (which, it is evident, can be readily exceeded, within the capability of the present device, with better test equipment), the laser pulses, for the conditions set forth, have a half-power pulse width of less than about 100 picoseconds. By adjusting the relative signal amplitude (e.g. by controlling bias and/or the AC signal amplitude and/or load), the pulse width can be advantageously controlled. The graph 15(d) shows the optical output power spectrum for this case.

Figure 16 is a diagram of an example of a circuit that can be used to operate the light emitting transistor (LET) 1610, under various conditions, including
conditions employed in examples of embodiments hereof. In this example, a controllable oscillator 1615 is coupled to the base terminal of the LET via a bias tee 1620, and the middle branch of the bias tee 1620 is coupled to a controllable bias voltage $V_{BE}$. The emitter terminal is coupled to ground reference potential and the collector terminal is coupled, via a bias tee 1640, to a variable load resistor 1660. The middle branch of the bias tee 1640 is coupled to controllable bias potential $V_{CE}$.

The graph of Figure 17, which also illustrates exemplary electrical input (above the graph), electrical output (below the graph), and optical output (on the right side of the graph), shows how three different output DC bias conditions can be used to generate optical outputs with controllable pulse widths. Figure 19 shows the three electrical and optical outputs, for the three respective operating points, plotted together.

In typical transistor operation, one of the three terminals of a transistor is common to both the input and output circuits. This leads to familiar configurations known as common emitter (CE), common base (CB), and common collector (CC). The common terminal (often ground reference) can be paired with one or the other of the two remaining terminals. Each pair is called a port, and two pairs for any configurations are called a two-port network. The two ports are usually identified as an input port and as an output port. As described in the referenced PCT Publication WO 2005/020287, and as illustrated in Figure 20, a third port, namely an optical output port, is provided, and is based on (recombination-radiation) emission from the base layer of the HBT light emitter. For the HBT of Figure 1 operated, for example, with a common emitter configuration, when an electrical signal is applied to the input port (Port 1), there results simultaneously an electrical output with signal amplification at Port 2 and optical output with signal modulation of light emission at Port 3.

As described in the referenced PCT Publication WO 2005/020287, Figure 21 illustrates the three terminal light emitting HBT, 910, in a lateral cavity, represented at 920, for operation as a lateral gain guided laser. The lateral cavity may be defined, for example, by cleaved edges on or near the light emitting region.
As described in the referenced PCT Publication WO 2005/020287, stimulated emission can be employed to advantage in the base layer of a bipolar transistor (e.g. a bipolar junction transistor (BJT) or a heterojunction bipolar transistor (HBT)), in order to enhance the speed of the transistor. Spontaneous emission recombination lifetime is a fundamental limitation of bipolar transistor speed. The base layer of a bipolar transistor is adapted to enhance stimulated emission (or stimulated recombination) to the detriment of spontaneous emission, thereby reducing recombination lifetime and increasing transistor speed. In a form of this aspect of the invention, at least one layer exhibiting quantum size effects, preferably a quantum well or a layer of quantum dots, preferably undoped or lightly doped, is provided in the base layer of a bipolar transistor. Preferably, at least a portion of the base layer containing the at least one layer exhibiting quantum size effects, is highly doped, and of a wider bandgap material than said at least one layer. The at least one quantum well, or layer of quantum dots, within the higher gap highly doped material, enhances stimulated recombination and reduces radiative recombination lifetime. A two-dimensional electron gas ("2-DEG") enhances carrier concentration in the quantum well or quantum dot layer, thereby improving mobility in the base region. Improvement in base resistance permits reduction in base thickness, with attendant reduction of base transport time. These advantages in speed are applicable in high speed bipolar transistors in which light emission is utilized, and/or in high speed bipolar transistors in which light emission is not utilized. In light emitting bipolar transistor devices, for example heterojunction bipolar transistors of direct bandgap materials, the use of one or more layers exhibiting quantum size effects can also be advantageous in enhancing light emission and customizing the emission wavelength characteristics of the devices. Doped or highly doped quantum size regions can also be utilized.

Figure 22 shows the use of one or more quantum wells, 141, 142, in the base region 140 of the Figure 1 device (or other embodiments). As described in the referenced PCT Publication WO 2005/020287, these quantum wells are operative to enhance the recombination process for improved device speed, modulation characteristics, and/or to tailor the spectral characteristics of the device. In one embodiment, the quantum well(s) (and/or dots – see below) are of
lower bandgap than the surrounding base layer (140) material and are undoped or lightly doped (e.g. below about $10^{16}$ cm$^{-3}$). The surrounding base layer (140) material is highly doped (e.g. uniformly or delta doped to at least about $10^{18}$ cm$^{-3}$ for p-type or at least about $10^{17}$ cm$^{-3}$ for n-type). In one embodiment, the quantum well (or dot) layer(s) have a thickness not greater than about 100 Angstroms.

As described in the referenced PCT Publication WO 2005/020287, a cavity with reflectors can be utilized laterally (e.g. Figure 21) or vertically (e.g. Figures 24 and 25) to obtain controlled laser operation of a light emitting HBT. As summarized above, enhancing stimulated emission can reduce recombination lifetime, to increase speed of operation.

Figure 23 shows use of one or more regions of quantum dots, 143, 144, in the base region 140 of the Figure 1 device (or other embodiments), these quantum dot regions being operative, as described in the referenced PCT Publication WO 2005/020287, to enhance the recombination process for improved device speed, modulation characteristics, and/or to tailor the spectral characteristics of the device. A combination of a quantum well 145, spaced apart from a layer of quantum dots 146 (see U.S. Patent 6,753,273), can also be utilized in the base region of devices hereof, as shown in Figure 24.

Figure 25 shows a vertical cavity surface emitting laser as described in the referenced PCT Publication WO 2005/020287, which employs light emission from the base region of an HBT. A substrate 1105 is provided, and the following layers are provided thereon. DBR reflector layer 1108, subcollector 1110, collector 1130, transition layer 1133, base 1140, emitter 1150, emitter cap layer 1160 and top DBR reflector layer 1168. Also shown are collector metallization 1115, base metallization 1145, and emitter metallization 1165. Collector lead 1117, base lead 1147, and emitter lead 1167 are also shown. In a form of this embodiment, the layers were grown by MOCVD, the substrate 1105 is a semi-insulating InP substrate, subcollector 1110 is n+ InGaAs, collector 1130 is n- InP, the base 1140 is a p+ InGaAs layer with a quantum well, the emitter 1150 is n-type InP, and the emitter cap 1160 is n+ InGaAs. Also, the transition layer is an n-type quaternary transition layer, for example InGaAsP. In this embodiment, the reflector layers 1108 and 1168 are multiple layer DBR reflectors, which can be spaced apart by
suitable distance, such as a half wavelength. In operation, as before, with signals applied in three terminal mode, modulation of the base current produces modulated light emission, in this case vertically emitted laser light represented by arrow 1190. As noted in the referenced PCT Publication WO 2005/020287, other configurations and material systems can be used, including, as examples, GaAs and GaN based HBTs, or other direct bandgap material systems. Also, the base layer 1140 can be provided with quantum well(s) or dot layer(s), as described elsewhere herein.

Figure 26 shows a further embodiment of a vertical cavity surface emitting laser, as described in the referenced PCT Publication WO 2005/020287, which has a Bragg reflector as close as possible to the collector and with elimination of intervening lower gap absorbing layers between the DBRs. In particular, in Figure 25 (which has like reference numerals to Figure 1 for corresponding elements), the lower DBR is shown at 111, and an upper DBR is shown at 143. Arrow 190 represents the optical standing wave of the VCSEL. The DBR 143 can be a deposited Si-SiO₂ Bragg reflector. A further reflector can also be provided on the top of emitter 150. Again, the base layer 140 can be provided with quantum well(s) or dot layer(s), as described elsewhere herein.

Figures 27, 28, 29, and 30 show devices and systems in accordance with further embodiments of the invention and which can be used in practicing embodiments of the method of the invention. In many respects, the devices of Figures 27-30 can be similar to light-emitting bipolar transistor devices as disclosed hereinabove, but with the improvements regarding the base region and its contacts, the associated electrical circuitry, and the resultant optical outputs. Accordingly, the embodiments to be described can employ any of the types of layer configurations that have been set forth or referenced, as well as other suitable configurations. For ease of illustration, only some of the basic device layers are illustrated in the Figures 27-30, and the laser cavity reflectors are implied.

The Figure 27 embodiment shows a heterojunction bipolar laser transistor that includes substrate 210, subcollector 230, collector 240, collector electrode 245, base 250, emitter 260, emitter cap 270, and emitter electrode 275. Potentials designated $V_E$ and $V_C$ are respectively coupled with the emitter and collector
electrodes. An optical coupling 202, such as a fiber optical coupling is coupled with the base region, and the laser output, most of all or which is actually input to the optical coupling, is illustrated at 205, it being understood that the side of the device opposite the optical coupling 202 will actually reflect most of the laser output that would otherwise exit as shown.

In the embodiment of Figure 27, a pair of spaced-apart base electrodes, 911 and 912, contact the base region 250. In the present example, the device is biased in forward active mode; that is, as described in the referenced prior applications, with forward-biased base-emitter junction and reverse-biased base-collector junction. In the present embodiment, a signal generator 921 produces a first signal at a frequency $f_1$, which is applied to base electrode 911, and a signal generator 922 produces a second signal at a different frequency, $f_2$, which is applied to base electrode 912. In this embodiment, the signals are relatively small sinusoidal and/or square wave microwave signals. The base current is maintained higher than the device threshold current (see the referenced PCT Publication WO 2005/020287), are coupled with each other. For the signals at frequencies $f_1$ and $f_2$, output frequencies, including beat frequencies, are expected to be observed at $f_1$, $f_2$, $f_1+f_2$, $|f_1-f_2|$, $2f_1+f_2$, $2f_2+f_1$, $|2f_1-f_2|$, $|2f_2-f_1|$, and so on. Output optical pulses with frequencies 10 GHz and well beyond are produced. It will be understood that the mixing of microwave signals to obtain up and down frequency conversion for modulated transistor laser output has particular advantage for various applications, including, for example, communications and optoelectronic integrated circuits.

The embodiment of Figure 28 has the outputs of voltage controlled oscillators 1021 and 1022 coupled with the respective base electrodes 911 and 912. In this embodiment, each of the voltage controlled oscillators 1021 and 1022 receives a respective control signal, on respective lines 1021A and 1022A. As described in conjunction with the previous embodiment, when the frequencies input to the respective base electrodes are $f_1$ and $f_2$, output frequencies, including beat frequencies, are expected to be observed at $f_1$, $f_2$, $f_1+f_2$, $|f_1-f_2|$, $2f_1+f_2$, $2f_2+f_1$, $|2f_1-f_2|$, $|2f_2-f_1|$, and so on. By inputting suitable control signals, the advantage of flexible tunability is achieved.
The embodiment of Figure 29 includes signal sources 921 and 922 as in Figure 9, but in this embodiment the output of signal generator 921 is coupled to the base electrode 911 via phase shifter 1150. The phase shift implemented by block 1150 is controlled by an input on line 1150A, and can range from 0 degrees to 360 degrees to achieve phase shift modulation mixing in the output laser.

Although two base electrodes are illustrated in the foregoing embodiments, it will be understood that other suitable pluralities of base electrodes can be employed with some or all having independent control. In the embodiment of Figure 30, for example, four input signals, from sources 911, 912, 913 and 914, are respectively coupled with base electrodes designated 921, 922, 923, and 924.

The embodiments of Figures 27-30 illustrate operation in terms of an edge-emitting bipolar transistor, but it will be understood that each of the embodiments can be implemented in conjunction with a vertical cavity bipolar transistor, such as those of Figures 25 or 26. Figure 31 shows the device of Figure 26, but with segmented base metallizations 1345 and 1346. Respectively coupled therewith are the outputs of signal generators 1321 and 1322, operating at frequencies f1 and f2, respectively (as in Figure 27). It will be understood that analogs of the embodiments of Figures 28-30, in the context of vertical cavity emitting bipolar devices, can also be implemented. Further, if suitable reflectors are provided for both edge emission and vertical emission, devices can be adapted for operation that switches between edge emitting and vertical emitting modes.

Figure 32 is a simplified diagram of the layer structure for another embodiment of the invention. The substrate 3110 can be undoped or doped, and has deposited thereon n-type cladding layer 3115, n-type collector contact layer 3120, a first tunnel junction 3125, p-type sub-collector 3130 and collector 3131 (which can be intrinsic or lightly doped p-type), n-type base 3140 containing at least one quantum size layer 3145 (e.g. quantum well and/or quantum dot layer(s)), p-type emitter 3160, second tunnel junction 3170, n-type upper cladding layer 3180, and n-type emitter contact layer 3190. When this Figure 32 embodiment is employed as an edge-emitting p-n-p heterojunction bipolar transistor (HBT) laser, the waveguide region (bracket 3150) can be enclosed in an optical resonant cavity of width w equal to n\lambda/2, with n = 1,2,3,..., and \lambda the
characteristic emission wavelength. Note that the tunnel junctions 3125 and 3170 are preferably outside the active base region. In this embodiment, the first tunnel junction 3125 includes a layered n+/p+ region with the n+ layer of the n+/p+ region being coupled with the collector contact layer 3120, and the p+ layer of the n+/p+ region being coupled with the collector 3131, via sub-collector 3130. Also in this embodiment, the second tunnel junction 3170 includes a layered n+/p+ region with the n+ layer of the n+/p+ region being coupled with the emitter contact layer 3190, via upper cladding 3180, and the p+ layer of the n+/p+ region being coupled with the emitter 3160.

The embodiment of Figure 33 can be employed as a vertical cavity p-n-p heterojunction bipolar transistor (HBT) laser, by providing vertically oriented waveguide 3250 within upper (3295) and lower (3205) DBRs, with waveguide dimension nλ/2, with n = 1,2,3,..., and λ the characteristic emission wavelength. In the Figure 33 embodiment, the further layers include the following: Substrate 3210 has deposited thereon the lower DBR 3205, n-type collector contact layer 3220, first tunnel junction 3225, p-type sub-collector 3230 and collector 3231 (which, as above, can be intrinsic or lightly doped p-type), n-type base 3240 containing at least one quantum size layer 3245 (again, e.g. quantum well and/or quantum dot layer(s)), p-type emitter 3260, second tunnel junction 3270, n-type emitter contact layer 3290, and the upper DBR 3295. In this embodiment, as before, the first tunnel junction 3225 includes a layered n+/p+ region with the n+ layer of the n+/p+ region being coupled with the collector contact layer 3220, and the p+ layer of the n+/p+ region being coupled with the collector 3231, via sub-collector 3230. The second tunnel junction 3270 of this embodiment includes a layered n+/p+ region with the n+ layer of the n+/p+ region being coupled with the emitter contact layer 3290, and the p+ layer of the n+/p+ region being coupled with the emitter 3260.

Figure 34 illustrates in further detail an example of the embodiment of Figure 1. The layered structure for this example is grown by MOCVD on a semi-insulating GaAs substrate 305. Upward from the substrate, the epitaxial layers of the crystal include a 3000 Å n-type heavily doped GaAs buffer layer 308, followed by a 634 Å n-type Al_{0.35}Ga_{0.65}As layer 316, a 5000 Å n-type Al_{0.95}Ga_{0.05}As layer 317, and a 200 Å n-type Al_{0.95}Ga_{0.05}As layer 318, forming the lower cladding layers.
These layers are followed by a 200 Å heavily doped n-type collector contact layer 320, and then a 120 Å heavily doped n-type In$_{0.49}$Ga$_{0.51}$P etch stop layer 322, and the tunnel junction 325, which includes a 200 Å heavily Si-doped n-type Al$_{0.10}$Ga$_{0.90}$As layer 326 and a 120 Å heavily C-doped p-type Al$_{0.10}$Ga$_{0.90}$As layer 327. Next are the subcollector and collector layers which comprise a 200 Å lightly doped p-type Al$_{0.10}$Ga$_{0.90}$As layer 330 and a 400 Å lightly doped p-type GaAs layer 331. In this example, there is a 1010 Å n-type GaAs base that includes eleven layers, three of which (represented collectively at 345) comprise a 190 Å InGaAs quantum well (QW) designed for emission at $\lambda \approx 1000$ nm. (These three layers comprise a 150 Å layer of In$_{0.2}$Ga$_{0.8}$As between 20 Å layers of In$_{0.1}$Ga$_{0.9}$As.) Starting after the last collector layer, the base layers are as follows: a 300 Å heavily Si doped n-type GaAs layer 341, a 10 Å undoped GaAs layer 342, followed by the previously described QW region 345, and then a 10 Å undoped GaAs layer 346, a 300 Å heavily Si doped n-type layer 347 and a 200 Å heavily doped n-type layer 348. Then, a 100 Å heavily Si-doped n-type GaAs layer is grown as a base contact layer 355. Subsequently, the following layers are grown: a heterostructure emitter comprised of a 150 Å $p$-type In$_{0.49}$Ga$_{0.51}$P layer 361 and a 200 Å $p$-type Al$_{0.35}$Ga$_{0.65}$As layer 362. This is followed by the tunnel junction 370, which includes a 150 Å heavily C doped $p$-type Al$_{0.35}$Ga$_{0.65}$As layer 371 and a 300 Å heavily Si doped n-type Al$_{0.35}$Ga$_{0.65}$As layer 372. Then, the upper confining or cladding region comprises a 150 Å $n$-type Al$_{0.80}$Ga$_{0.20}$As oxidation buffer layer 381, and a 4000 Å $n$-type Al$_{0.95}$Ga$_{0.05}$As oxidizable layer 382, a 300 Å $n$-type Al$_{0.80}$Ga$_{0.20}$As oxidation buffer layer 383, and a 500 Å $n$-type Al$_{0.35}$Ga$_{0.65}$As layer 384. The layered structure is capped with a 1000 Å heavily Si doped n-type GaAs emitter contact layer 390.

The process for fabricating the heterostructure bipolar pnp transistor laser continues by first patterning 4 μm protective SiN₄ stripes on the crystal with a photolithography step and reactive ion etching with Freon 14 (CF₄) gas. The top $n$-type GaAs contact layer 390 and Al$_{0.35}$Ga$_{0.65}$As transition layer 384 are then exposed by wet etching (1:8:80 H$_2$O$_2$:H$_2$SO$_4$:H$_2$O) to form a ~ 4 μm emitter mesa. Since 1:8:80 H$_2$O$_2$:H$_2$SO$_4$:H$_2$O wet etching solution is not selective to an Al$_{0.95}$Ga$_{0.05}$As layer, a precise (~20 s) time etching is used in this example to stop
at the interface of Al$_{0.95}$Ga$_{0.05}$As layer 383. Next, a wide 11 µm protective photoresist (PR) stripe is placed over the emitter mesa and the unprotected layers (362, 370, 381, and 382) are removed with 1:8:80 H$_2$O$_2$:H$_2$SO$_4$:H$_2$O selective wet etching solution, revealing the p-type In$_{0.49}$Ga$_{0.51}$P wide-gap emitter layer 361. The protective photoresist (PR) stripe is then removed and the sample is oxidized for 7 min at 425 °C in a furnace supplied with N$_2$+H$_2$O, resulting in a ~ 0.9 µm lateral oxidation which forms ~ 2.2 µm oxide-defined apertures in the 4 µm emitter mesa. The samples are annealed (in N$_2$) at 425 °C for 7 minutes to re-activate p-dopants before the protective SiN$_4$ is removed by plasma (CF$_4$) etching. The emitter layer (361) In$_{0.49}$Ga$_{0.51}$P, is then removed using a wet etch (HCl), exposing the n-type GaAs base contact layer 355. A 37 µm PR window, is then patterned to form the base mesa for the base contact. The layers from 326 to 355 are then removed using a selective etch (10:1 C$_6$H$_8$O$_7$:H$_2$O$_2$), and the In$_{0.49}$Ga$_{0.51}$P etch-stop layer 322 is removed by a wet etch (HCl), exposing the heavily doped n-type GaAs collector contact layer 320. Subsequently, a 5 µm PR window is formed over the base mesa, a 7 µm PR window is formed over the emitter mesa and oxide layer, and a 20 µm PR window is formed over the collector material to deposit AuGe/Ni/Au (750/150/10000 Å) to form, simultaneously, n-type metal contacts to the emitter contact layer 390, base contact layer 355 and collector contact layer 320. After the metal lift-off step, the sample is then annealed at 350 °C to form ohmic contacts. Then, a layer of polyimide is applied and cured at 270 °C to reduce the surface leakage current of the device. An additional layer of silicon nitride is deposited on top of the polyimide using a plasma-enhanced chemical vapor deposition (PECVD) system. Via hole openings to create contacts to emitter, base, and collector metals are defined using another photolithography step. Using Freon 14 (CF$_4$) gas and PR as an etch mask, the dielectric via opening to the silicon nitride layer is performed with a reactive ion etching (RIE) system. The PR is then stripped with cleaning solvents. Oxygen (O$_2$) plasma is used to remove the polyimide layer, the silicon nitride layer acting as an etch mask. After the contact via fabrication step, another photolithography step is performed to deposit Ti/Au (150 Å/ 2.5 µm) to form contacts from the device to ground-signal-ground (GSG) high frequency probing pads. The GSG probe pads are designed,
in this example, as 400 μm cells so that multiple integer resonator lengths of 400 μm can be cleaved for device fabrication. The sample is then lapped to a thickness of ~ 50 μm. The HBTL samples are cleaved normal to the emitter stripes to form Fabry-Perot facets (at multiples of ~ 400 μm), and the substrate side of the crystal is alloyed onto Cu heat sinks coated with In for device operation.

Figure 35 shows the edge-emitting pnp HBT transistor laser with tunnel junction contacts on the p-type emitter and p-type collector. The device has the general layer structure of the Figure 32 embodiment, with metal contacts shown (collector contact 3121, base contact 3155, and emitter contact 3191), and the electron and hole current paths also illustrated. As in Figure 32, the layer structure for this example includes substrate 3110, n-type lower cladding 3115, n-type collector contact layer 3120, first tunnel junction 3125, p-type sub-collector 3130, p-type collector 3131, n-type base 3140 (with QW), p-type emitter 3160, second tunnel junction 3170, n-type upper cladding 3180, and n-type emitter contact layer 3190. As represented in the diagram by the darkened arrows 490 and 420, respectively, electron current is shown flowing, in n-type material, from the emitter contact to second tunnel junction 3170, and, in n-type material, from the first tunnel junction 3125 to the collector contact. Also, the electron current flow in the n-type base is represented by darkened arrow 440. As seen, the second tunnel junction 3170 operates to convert electron current to hole current (lighter arrow 470), and the first tunnel junction 3125 operates to convert hole current to electron current. In this manner, the relatively advantageous electron current in the n-type emitter contact layer and upper cladding, and also in the n-type collector contact layer, replaces what would otherwise be less efficient hole current in p-type material in a conventional pnp device.
CLAIMS:

1. A method for producing controllable light pulses, comprising the steps of:
   providing a heterojunction bipolar transistor structure comprising collector, base, and emitter regions of semiconductor materials;
   providing an optical resonant cavity enclosing at least a portion of said transistor structure; and
   coupling electrical signals with respect to said collector, base, and emitter regions, to switch back and forth between a stimulated emission mode that produces output laser pulses and a spontaneous emission mode.

2. The method as defined by claim 1, wherein said electrical signals include an AC excitation signal, and wherein part of each excitation signal cycle is operative to produce stimulated emission, and another part of each excitation signal cycle is operative to produce spontaneous emission.

3. The method as defined by claim 2, wherein, during said part of said cycle, the current in the base region exceeds the stimulated emission threshold of said device, and during said other part of said cycle, the current in the base region does not exceed said threshold.

4. The method as defined by claim 3, further comprising controlling the frequency of said excitation signal to control the frequency of said output laser pulses and controlling the relative amplitude of said excitation signal to control the pulse width of said output laser pulses.

5. The method as defined by claim 3, further comprising controlling the relative amplitude of said excitation signal to control the pulse width of said output laser pulses.

6. The method as defined by claim 2, further comprising providing said AC excitation signal at a frequency of at least about 1 GHz.

7. The method as defined by claim 2 or 4, further comprising providing said AC excitation signal at a frequency of at least about 3 GHz.

8. The method as defined by claim 4 or 5, wherein said pulse width is controlled to have a pulse width of less than about 100 picoseconds.
9. Apparatus for producing controllable light pulses, comprising:
   a heterojunction bipolar transistor structure comprising collector,
   base, and emitter regions of semiconductor materials;
   an optical resonant cavity enclosing at least a portion of said
   transistor structure; and
   means for coupling electrical signals with respect to said collector,
   base, and emitter regions, to switch back and forth between a stimulated emission
   mode that produces output laser pulses and a spontaneous emission mode.

10. Apparatus as defined by claim 9, wherein said electrical signals include
   an AC excitation signal, and wherein part of each excitation signal cycle is
   operative to produce stimulated emission, and another part of each excitation
   signal cycle is operative to produce spontaneous emission.

11. Apparatus as defined by claim 10, wherein, during said part of said
    cycle, the current in the base region exceeds the stimulated emission threshold of
    said device, and during said other part of said cycle, the current in the base region
    does not exceed said threshold.

12. Apparatus as defined by claim 9, further comprising means for
    controlling the frequency of said excitation signal to control the frequency of said
    output laser pulses and controlling the relative amplitude of said excitation signal to
    control the pulse width of said output laser pulses.

13. Apparatus as defined by claim 9, further comprising means for
    controlling the relative amplitude of said excitation signal to control the pulse width
    of said output laser pulses.

14. Apparatus as defined by claim 10, further comprising means for
    providing said AC excitation signal at a frequency of at least about 1 GHz.

15. Apparatus as defined by claim 10 or 13, further comprising means for
    providing said AC excitation signal at a frequency of at least about 3 GHz.

16. Apparatus as defined by claim 12, wherein said pulse width is controlled
    to have a pulse width of less than about 100 picoseconds.

17. A method for producing high frequency laser pulses, comprising the
    steps of:
providing a heterojunction bipolar transistor structure comprising collector, base, and emitter regions of semiconductor materials;

providing an optical resonant cavity enclosing at least a portion of said transistor structure; and

coupling electrical signals, at least some of which have a frequency of at least about 1 GHz, with respect to said collector, base, and emitter regions, to produce output laser pulses at a frequency of at least about 1 GHz.

18. The method as defined by claim 17, wherein at least some of said electrical signals have a frequency of at least about 3 GHz, and said output laser pulses have a frequency of at least about 3 GHz.

19. A method for determining the stimulated emission threshold of a light-emitting transistor device, comprising the steps of:

providing a heterojunction bipolar transistor structure comprising collector, base, and emitter regions of semiconductor materials;

providing an optical resonant cavity enclosing at least a portion of said transistor structure;

coupling electrical signals with respect to said collector, base, and emitter regions;

determining the differential current gain transistor structure as a function of the transistor base current; and

determining the stimulated emission threshold bas current of said transistor structure as the base current at which said differential current gain begins to decrease with increasing base current.

20. Apparatus for receiving first and second electrical signals and producing an optical output as a function of said first and second electrical signals; comprising:

a bipolar light-emitting transistor device that includes collector, base, and emitter regions;

a collector electrode coupled with said collector region and an emitter electrode coupled with said emitter region, whereby electrical potentials can be coupled with said collector and emitter regions;
an optical coupling in optical communication with said base region;
and
first and second base electrodes coupled with said base region;
said first and second electrical signals being respectively coupled
with said first and second base electrodes, whereby an optical output, which is a
function of said first and second electrical signals, is emitted from said base region
and coupled into said optical coupling.

21. Apparatus as defined by claim 20, wherein said base region is within an
optical resonant cavity that includes a reflector that is at least partially reflective of
optical radiation, and wherein said optical output comprises laser output.

22. Apparatus as defined by claim 20 or 21, wherein said laser output
comprises a plurality of coupled laser beams.

23. Apparatus as defined by claim 20 or 22, wherein said first electrical
signal has a frequency f1, said second electrical signal has a frequency f2, and
said optical output includes a frequency component from the group consisting of
f1+f2, |f1-f2|, 2f1+f2, 2f2+f1, |2f1-f2|, and |2f2-f1|.

24. Apparatus as defined by claim 20 or 21, wherein said optical coupling
comprises an optical fiber.

25. Apparatus as defined by claim 20, wherein said base region includes at
least one layer exhibiting quantum size effects.

26. Apparatus as defined by claim 20, wherein said at least one layer
exhibiting quantum size effects comprises at least one quantum well.

27. Apparatus as defined by claim 20 or 21, further comprising first and
second controllable oscillators for producing said first and second electrical signals.

28. Apparatus as defined by claim 20 or 21, further comprising a signal
generator for producing said first and second electrical signals, and a phase shifter
for producing a phase shift between said first and second electrical signals.

29. A method for producing an optical output, comprising the steps of:
providing first and second electrical signals;
providing a heterojunction bipolar light-emitting transistor device that
includes collector, base, and emitter regions;
providing a collector electrode coupled with said collector region and an emitter electrode coupled with said emitter region, and coupling electrical potentials with respect to said collector and emitter electrodes;

providing an optical coupling in optical communication with said base region;

providing first and second base electrodes coupled with said base region; and

coupling said first and second electrical signals with said first and second base electrodes, respectively, to produce an optical output emitted from said base region and coupled into said optical coupling, said optical output being a function of said first and second electrical signals.

30. The method as defined by claim 29, wherein said step of providing a bipolar light-emitting transistor device comprises providing a laser transistor, and wherein said optical output comprises laser output.

31. The method as defined by claim 29 or 30, wherein said laser output comprises a plurality of coupled laser beams.

32. The method as defined by claim 29 or 30, wherein said first electrical signal has a frequency $f_1$, said second electrical signal has a frequency $f_2$, and said optical output includes a frequency component from the group consisting of $f_1 + f_2$, $|f_1 - f_2|$, $2f_1 + f_2$, $2f_2 + f_1$, $|2f_1 - f_2|$, and $|2f_2 - f_1|$.

33. The method as defined by claim 29 or 30, wherein said optical coupling comprises an optical fiber.

34. The method defined by claim 29 or 30, wherein said step of providing first and second electrical signals comprises providing first and second controllable oscillators for producing said first and second electrical signals.

35. The method as defined by claim 29 or 30, wherein said step of providing first and second electrical signals comprises providing a signal generator for producing said first and second electrical signals, and a phase shifter for producing a phase shift between said first and second electrical signals.
36. Apparatus for receiving a plurality of electrical signals and producing an optical output as a function of said plurality electrical signals; comprising:
   a bipolar light-emitting transistor device that includes collector, base, and emitter regions;
   a collector electrode coupled with said collector region and an emitter electrode coupled with said emitter region, whereby electrical potentials can be coupled with said collector and emitter regions;
   an optical coupling in optical communication with said base region;
   and
   a plurality of electrodes coupled with said base region;
   said plurality of electrical signals being respectively coupled with said plurality of base electrodes, whereby an optical output, which is a function of said first and second electrical signals, is emitted from said base region and coupled into said optical coupling.

37. Apparatus as defined by claim 36, wherein said plurality of electrical signals comprises four electrical signals, and said plurality of base electrodes comprises four electrodes.

38. Apparatus as defined by claim 36 or 37, wherein said transistor device is a laser device, and said optical output is a laser output.

39. Apparatus as defined by claim 38, wherein said optical coupling comprises an optical fiber.

40. Apparatus as defined by claim 36, wherein said transistor is an edge emitting laser device, and said optical output is a laser output.

41. Apparatus as defined by claim 36, wherein said transistor is vertical cavity laser device, and said optical output is a laser output.

42. A semiconductor light-emitting transistor device, comprising:
   a bipolar pnp transistor structure having a p-type collector, an n-type base, and a p-type emitter;
   a first tunnel junction coupled with said collector, and a second tunnel junction coupled with said emitter; and
a collector contact coupled with said first tunnel junction, an emitter contact coupled with said second tunnel junction, and a base contact coupled with said base;

whereby, signals applied with respect to said collector, base, and emitter contacts causes light emission from said base by radiative recombination in said base.

43. The device as defined by claim 42, wherein said first tunnel junction comprises a layered n+/p+ region with the n+ layer of said n+/p+ region being coupled with said collector contact and the p+ layer of said n+/p+ region being coupled with said collector.

44. The device as defined by claim 42, wherein said collector comprises collector layer coupled with said base and a p-type sub-collector layer coupled with said collector contact.

45. The device as defined by claim 44, wherein said collector layer is intrinsic or lightly doped p-type.

46. The device as defined by claim 42 or 43, wherein said second tunnel junction comprises a layered n+/p+ region with the n+ layer of said n+/p+ region being coupled with said emitter contact and the p+ layer of said n+/p+ region being coupled with said emitter.

47. A semiconductor laser device comprising the semiconductor light-emitting transistor device as defined by claim 42, 43, or 46, further comprising an optical resonant cavity enclosing at least a portion of said base of said device.

48. The laser device as defined by claim 47, wherein at least a portion of said device is in layered form, and wherein said optical resonant cavity is a lateral cavity with respect to the layer plane of said at least a portion of said device.

49. The laser device as defined by claim 47, wherein at least a portion of said device is in layered form, and wherein said optical resonant cavity is a vertical cavity with respect to the layer plane of said at least a portion of said device.

50. The device as defined by claim 42, wherein said transistor comprises a heterostructure of direct bandgap semiconductor material.
51. The device as defined by claim 50, wherein said base of said device comprises a heavily doped n+ region.

52. The device as defined by claim 50, further comprising a region in said base exhibiting quantum size effects.

53. The device as defined by claim 52, wherein said region in said base exhibiting quantum size effects comprises a quantum well layer.

54. The device as defined by claim 52, wherein said region in said base exhibiting quantum size effects comprises a layer of quantum dots.

55. A method for producing light modulated with an input electrical signal, comprising the steps of:

   providing a bipolar transistor device that includes a p-type collector, an n-type base, and a p-type emitter;
   providing a first tunnel junction coupled with said collector, and a second tunnel junction coupled with said emitter;
   providing a collector contact coupled with said first tunnel junction, and providing an emitter contact coupled with said second tunnel junction, and providing a base contact coupled with said base;
   applying electrical signals with respect to said collector, base, and emitter contacts to cause light emission by radiative recombination in the base region; and
   controlling the base current of said transistor device with said input electrical signal to modulate the light emission from said transistor device.

56. A semiconductor transistor device, comprising:

   a bipolar npn transistor structure having a p-type collector, an n-type base, and a p-type emitter;
   a first tunnel junction coupled with said collector, and a second tunnel junction coupled with said emitter; and
   a collector contact coupled with said first tunnel junction, an emitter contact coupled with said second tunnel junction, and a base contact coupled with said base;
whereby, signals applied with respect to said collector, base, and emitter contacts causes light emission from said base by radiative recombination in said base.

57. The device as defined by claim 56, wherein said first tunnel junction comprises a layered n+/p+ region with the n+ layer of said n+/p+ region being coupled with said collector contact and the p+ layer of said n+/p+ region being coupled with said collector.

58. The device as defined by claim 56, wherein said collector comprises collector layer coupled with said base and a p-type sub-collector layer coupled with said collector contact.

59. The device as defined by claim 58, wherein said collector layer is intrinsic or lightly doped p-type.

60. The device as defined by claim 56 or 57, wherein said second tunnel junction comprises a layered n+/p+ region with the n+ layer of said n+/p+ region being coupled with said emitter contact and the p+ layer of said n+/p+ region being coupled with said emitter.
FIG. 4
Energy (eV)

InGaP-GaAs-InGaAs QW HBLET Laser

Relative Intensity

Wavelength (nm)

(a) (b) (c)

6 mA

8

10

1020 970 920

FIG. 5
FIG. 6

FIG. 7
InGaP-GaAs-InGaAs Transistor Laser
3 GHz, $V_{CE} = 2$ V
$T = 213$ K
CW

(a) $I_B = 12$
(b) $5$ mA

FIG. 8
Transistor Laser

Optical Fiber

Laser Beam

200µm

FIG. 9
InGaP-GaAs-InGaAs Transistor Laser
$V_{CE} = 2\, \text{V}, \, I_B = 9\, \text{mA}$

(a) Electrical Input (Port 1)

(b) Electrical Output (Port 2)

(c) Optical Output (Port 3)

Time (ns)

FIG. 10
FIG. 11

FIG. 12

SUBSTITUTE SHEET (RULE 26)
FIG. 13a

FIG. 13b

FIG. 13c

FIG. 13d
FIG. 14a

FIG. 14b

FIG. 14c
FIG. 17
16 / 30

Electrical Output

FIG. 18

Optical Output

FIG. 19

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FIG. 20

FIG. 21
FIG. 32
FIG. 34

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FIG. 35
3191 Metal Contact
3190
3180
(B)
3155 Metal Contact
440 Electron
3131 Collector (intrinsic or lightly doped)
3130 Sub-Collector (p-type)
1st Tunnel Junction
3120 Collector Contact Layer (n-type)
420 Electron
Lower Cladding (n-type)
3115
3110
(C)
3121 Metal Contact
3125
3140 Base (n-type) +QW
3170 2nd Tunnel Junction
3160 Emitter (p-type)
3170 Upper Cladding (n-type)
490 Electron