Bistability and negative resistance in semiconductor lasers

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Experimental results of a buried heterostructure laser with a segmented contact to achieve inhomogeneous gain are presented. Measurements reveal a negative differential resistance over the absorbing section. Depending on the source impedance of the dc current source driving the absorbing section, this negative resistance can lead to (i) bistability with a very large hysteresis in the light-current characteristic *without* self-pulsation or (ii) a small hysteresis with self-pulsations at microwave frequencies. An analysis, which includes the electrical part of the device, leads to an explanation of self-pulsations in inhomogeneously pumped lasers without having to rely on a sublinear gain dependence on injected carrier concentration.

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Semiconductor lasers with inhomogeneous excitation, such as the double contact structure,[1] have recently become objects of renewed interest as highly compact and efficient bistable optical devices. Bistable optical elements have important technological significance in the field of optoelectronic signal generation, detection, and processing. Unfortunately inhomogeneously pumped injection lasers to date showed none or only a small hysteresis.[2–4] In addition, these inhomogeneously pumped semiconductor lasers produced a pulsating light output[5–7] for reasons not well understood. Several authors [5,6,8] suggested a repetitively Q-switched mechanism by assuming a sublinear gain dependence on injected carrier concentration. The calculated[9] and measured[10–12] gain dependence in undoped or lightly doped GaAs, however, does not fulfill this necessary condition for pulsation.

In this letter we present experimental results on a bistable laser with a very large hysteresis in the light-current characteristic observed in a buried heterostructure (BH) laser with a two segment contact. This laser is identical to the one previously reported,[4] except that the resistance between the two segments has been substantially increased. In addition we measured a negative differential resistance which, when external biasing circuit elements are taken into account, can explain regimes of bistability with a very large hysteresis *without* self-pulsations, or a small hysteresis with self-pulsations at microwave frequencies in lasers with inhomogeneous injection and offers new insight into the statics and dynamics of nonuniformly pumped lasers.

The cw threshold current for a uniformly pumped device, 250 μm long, is typically between 15 and 20 mA. The lasers have been fabricated by a standard process[13] in our laboratory. A 20 μm-wide stripe is etched into the p-contact metallization before the wafer is cleaved into the single devices. The upper cladding layer of the BH laser is only slightly p doped in order to increase the parasitic resistance R_p between the two contact pads, measured to be around 60 kΩ. It will be shown below that a very good electrical separation between the two segments is essential for the operation of the bistable laser. Nearfield and farfield measurements show that the device is lasing over its complete operating range in the fundamental transverse mode, demonstrating the effectiveness of the dielectric waveguide. The use of the BH structure makes it thus possible to isolate and study the effects of inhomogeneous excitation in the cw regime with a device whose optical and electronic properties are stable and simple.

With both sections pumped equally, the light-current characteristic is linear as shown in Fig. 1, curve (a). I_{th} is the total threshold current into both sections. For bistable operation, the absorber section (the section which is 100 μm long) is pumped with a constant current I_2 from a current source whose equivalent source impedance is $R_2 = 400$ kΩ. The light output for this operation is shown in Fig. 1 as a function of I_1, the current injected into the gain section. For $I_2 = -110\,\mu$A the laser diode switches to the lasing state if I_1 is increased above 30 mA. The light output is stable in this

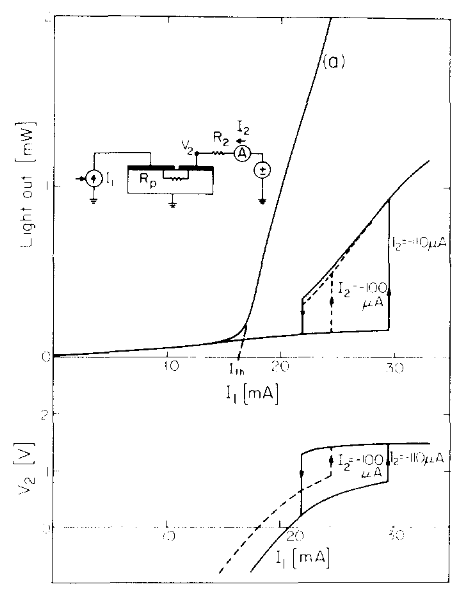

FIG. 1. dc characteristic of the double contact laser. In the upper part of the figure the optical power output per mirror is plotted as a function of the drive current I_1 for two different bias currents $I_2 = -100\,\mu$A and $I_2 = -110\,\mu$A through the absorber section. The source impedance is $R_2 = 400$ kΩ and the parasitic resistance $R_p = 60$ kΩ. Curve (a) shows for comparison the characteristic for the homogeneously pumped laser. In the lower part V_2, the voltage over the current driven absorber section is plotted as a function of I_1.

state, and no pulsation is observed. If I_1 is now decreased the diode continues to lase and switches off at $I_1 = 22$ mA. Note that I_2 is negative, that is, carriers are swept out of the absorbing region. The light-current characteristic with $I_2 = -100\,\mu$A (dashed line) is also shown in Fig. 1 and displays the sensitivity of the hysteresis on the degree of inhomogeneous injection.

The voltage V_2 across the absorber section is shown in the lower part of Fig. 1. For the cycle of I_1 described above, the voltage V_2 increases steadily to about 0.8 V. As soon as the device starts to lase, the absorbing section becomes bleached and the voltage jumps to 1.45 V, the band-gap voltage of GaAs. Decreasing I_1 causes V_2 to drop at first only slightly and then to jump back to 0.2 V when the laser switches off.

The behavior of the double contact laser depends dramatically on the source impedance driving the absorber section. With a large source impedance, $R_2 = 200$ kΩ, the laser behaves as described above. If the absorber section is driven with a source impedance of 1 kΩ, the hysteresis in the light-current characteristic is reduced drastically as shown in Fig. 2 and the light output self-pulsates at very high frequencies between 500 MHz and 2GHz depending on the pump current I_1 as reported earlier.[4]

Another imporant and physically revealing observation involves the variation of the voltage V_2 across the absorber section as function of I_2. The resulting characteristic is shown in Fig. 3 with I_1 as parameter. For $V_2 = 0$, the device does not lase and the absorbing region acts as a photodiode collecting the spontaneous emission from the gain section which results in a photocurrent of $I_2 = -100\,\mu$A. As V_2 is increased, the current (I_2) dependence is similar to an ordinary photodiode. The device starts to lase around $V_2 = 1.0$ V and the photocurrent in the absorbing section increases. With further increase of the applied voltage V_2, I_2 is reduced

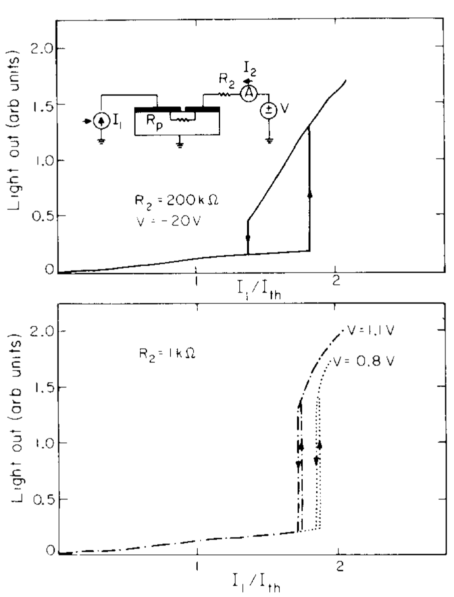

FIG. 2. Light-current characteristic as a function of I_1/I_{th} for two different source impedances R_2. The parasitic resistance between the two sections is $R_p = 60$ kΩ. I_{th} is the threshold of the homogeneously pumped laser as defined in Fig. 1.

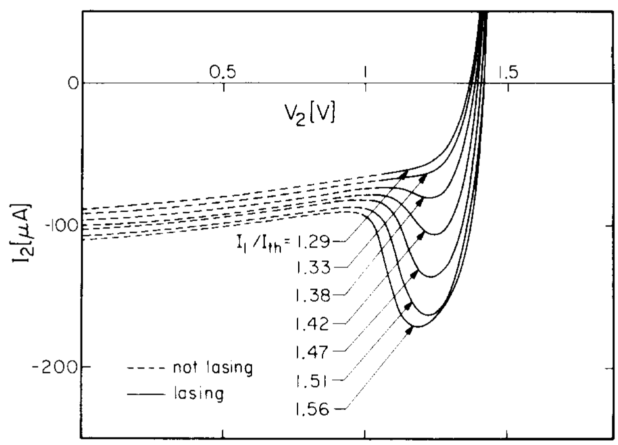

FIG. 3. Current-voltage characteristic of the absorber section for different pump currents in the gain section I/I_{th}.

and becomes positive for $V_2 \geqslant 1.4$ V. The group of curves in Fig. 3 has a region of negative differential resistance between $V_2 = 1.0$ V and 1.2 V, very similar to a tunnel diode.

We shall now show how this observed I-V characteristic of the absorbing section, when combined with those of the external bias circuit, can explain the different regimes of bistability or self-pulsation. The I-V characteristic of the absorber section is shown again in Fig. 4 together with the characterization of the source driving this section, which is given by the load line. This line shows the voltage available to the absorber section as a function of the current through it. The state of the system satisfying all circuit equations is given by the intersection of the load line with the I-V characteristic of the absorber section. R_L is the effective resistance loading the absorbing section. The bias point P_1 corresponds to the case when the absorbing section is biased by a source $V = -1$ V with an effective resistance of 20 kΩ, and the gain section is pumped with $I_1/I_{\text{th}} = 1.29$. Increasing I_1 causes the state of the absorbing section to move along the load line from P_1 to P_2 and at $I_1/I_{\text{th}} > 1.56$ to jump to P_3, since this is the only intersection of the load line and the absorber section characteristic. At this point the laser is switched on. A decrease of I_1 causes the state to move back to

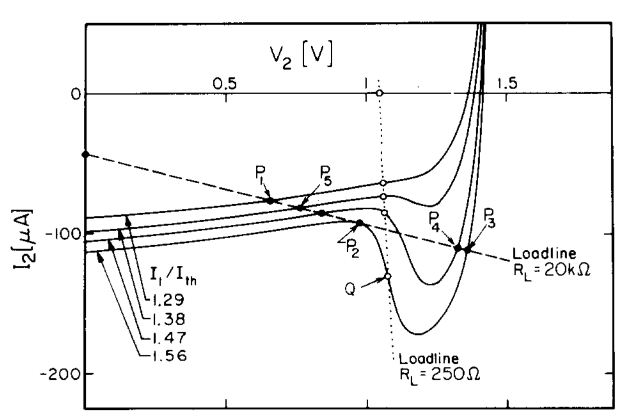

FIG. 4. Current-voltage characteristic of the absorber section for different pump currents in the gain section I_1/I_{th}. The dashed line represents the load line for a voltage source of $V = -1$ V with 20 kΩ effective load impedance; the dotted one is the load line for a voltage source of $V = +1.05$ V and 250 Ω effective load impedance.

P_4 and then to jump to P_5, which switches the laser off.

Biasing the absorbing section with a much lower impedance, for instance $R_L = 250\,\Omega$, forces the absorbing section to operate in a region of negative differential resistance. The resulting operating point Q is shown in Fig. 4 as the intersection of the dashed load line and the characteristic curve. This negative resistance leads to high frequency electrical oscillation and a concommitant light intensity pulsation. Since this negative resistance is not frequency selective, the pulsation takes place at the resonance frequency of a frequency selective element coupled to the negative resistance. Experiments show[4] that the light output oscillates around the relaxation frequency of the diode. The importance of having a large parasitic resistance R_p can now be appreciated, since the effective load resistance $R_L = R_p R_2/(R_p + R_2)$ (R_2 in parallel with R_p) is always smaller than R_2 or R_p.

A set of three rate equations, one for the electrons in the gain region, another one for those in the absorbing region, a third one for the photons with a *linear* gain dependence on carrier density and equations characterizing the electrical circuit, has been used to calculate the steady-state characteristics of the double contact laser. The calculated hysteresis and negative resistance are in reasonable agreement with our measured results and will be published in a forthcoming paper. A small signal analysis shows that two of the three zeroes of the characteristic equation are confined to the complex left half-plane. One real zero moves through the origin into the right half-plane at the switching point from the off to the on state. Since a zero at the origin corresponds to an infinite response time this device is expected to display critical slowing down. This has been observed and will be discussed separately.[14]

In conclusion, we have shown that a double contact laser can be made to display a large hysteresis in the light-current characteristics when the gain and loss section are electrically insulated. This bistable device does not pulsate intrinsically, indicating that the absorber does not saturate much more easily than the gain, in agreement with measurements.[12] We measured a negative differential resistance in the absorber section. In addition it has been demonstrated that the device can be forced into a bistable state, a very high differential quantum efficiency state or a self-pulsating regime, depending on the choice of the load impedance at the absorber section. The inclusion of the electrical aspect of the semiconductor laser makes it possible to explain the observed self-pulsations in inhomogeneously pumped lasers without having to rely on an unrealistic sublinear gain dependence on injected carrier concentration.

This bistable device should find applications in the field of electro-optical signal processing and we will report separately on the important issues of the optical and electronic switching.[14] Although the emphasis in this letter is on the laser performance, the device may find application as a three terminal negative resistance circuit element.[14]

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