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# Self-pulsating lasers with quantum well saturable absorber

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Self-pulsations are induced in broad area diode lasers by including an extra layer functioning as a saturable absorber. The absorption of this layer and its coupling to the photon field can be tuned via the layer thickness and its distance to the active layer. In the case of an Al<sub>0.13</sub>GaAs bulk active layer a GaAs absorber of 4 nm thickness at a distance of 0.2 μm induces stable oscillations with frequencies of 300–700 MHz in a current range just above the threshold. © 1995 American Institute of Physics.

In some applications of diode lasers, e.g., disk readout, optical feedback can be a source of excessive noise. One way to avoid this is to modulate the laser output at a high pulse repetition rate. This can be achieved by adding a modulator, at the cost of complicating the circuit. Alternatively, one can try to induce self-pulsations by including a saturable absorber in the cavity.

In the past, this has been done by splitting the cavity in two longitudinal sections<sup>1</sup> or by using the fact that in narrow-stripe lasers the current spreading provides weakly pumped, that is absorbing, regions in the lateral tails of the optical mode.<sup>2</sup>

In this work, a new method is demonstrated, i.e., the inclusion of a saturable absorbing layer parallel to the active layer. One now has several design parameters, including the band gap and thickness of the absorbing layer as well as its distance to the active layer. With the present accuracy of organometallic vapor phase epitaxy (OMVPE) and molecular beam epitaxy (MBE) crystal growth techniques the thickness, composition, and positioning of the absorbing layer can be extremely well-controlled, thereby providing a very reproducible fabrication method for self-pulsating laser devices.

The idea is realized using a conventional broad-area GaAs/AlGaAs DH laser. The layer structure consists of a bulk active layer with a 13% AlAs mole fraction sandwiched between cladding layers of 50% AlAs. The active layer is 40 nm thick, the cladding 1.7 μm, see the inset of Fig. 3. To induce self-pulsations a GaAs absorbing layer is included inside one of the cladding layers. If the absorber is very thin it forms a quantum well and by adjusting its thickness  $t_{QW}$  the effective band gap can be set at values below or above the gap of the active layer. In this way, the intrinsic absorption can be adjusted over a large range of values. The coupling between the absorber and the photon field can be adjusted independently by varying the distance  $d$  to the active layer.

Because a broad-area laser is considered we can follow the approach of Basov,<sup>3</sup> Dixon and Joyce,<sup>4</sup> and Shou-Wu *et al.*,<sup>5</sup> neglecting the influence of the longitudinal and lateral

optical mode patterns. The transversal mode pattern is accounted for by two confinement factors  $\Gamma_{act}$  and  $\Gamma_{abs}$ , for the active layer and the absorbing layer, respectively. The behavior of this system is described by three rate equations for  $N_{act}$ ,  $N_{abs}$  and the photon density  $S$

$$\frac{\partial N_{act}}{\partial t} = \frac{J}{qd} - R(N_{act}) - c_s \Gamma_{act} g(N_{act}) S, \quad (1)$$

$$\frac{\partial N_{abs}}{\partial t} = -R(N_{abs}) + c_s \Gamma_{abs} \alpha(N_{abs}) S, \quad (2)$$

$$\frac{\partial S}{\partial t} = \left( c_s [\Gamma_{act} g(N_{act}) - \Gamma_{abs} \alpha(N_{abs})] - \frac{1}{\tau_p} \right) S + \beta [\Gamma_{act} R(N_{act}) + \Gamma_{abs} R(N_{abs})], \quad (3)$$

where  $\tau_p$  is the photon lifetime, including internal and mirror losses

$$\tau_p = c_s \left( \alpha_{int} + \frac{1}{2L} \ln \frac{1}{R_1 R_2} \right), \quad (4)$$

and the symbols have the following meaning:  $J$ : injection current density,  $d$ : active layer thickness,  $L$ : cavity length,  $c_s = c/n_{eff}$ : light velocity in the semiconductor,  $R(N)$ : carrier density dependent recombination terms including nonradiative and spontaneous-emission contributions,  $\beta$ : the fraction of the spontaneous emission coupled into the lasing mode.

The important parameters are the gain of the active layer  $g(N_{act})$  and the absorption  $\alpha(N_{abs})$  of the absorbing layer, where  $N_{act}$  and  $N_{abs}$  are the respective densities. In the active layer we assume equal electron and hole densities, in the absorbing layer  $N_{abs}$  indicates the minority carrier density. Consequently, in the active layer we use a bimolecular recombination term and in the absorbing layer a recombination time constant

$$R(N_{act}) = B N_{act}^2, \quad R(N_{abs}) = N_{abs} / \tau_{abs}. \quad (5)$$

The gain function of the bulk active layer is approximated by a linear function, but for the quantum well absorber a logarithmic function is more appropriate

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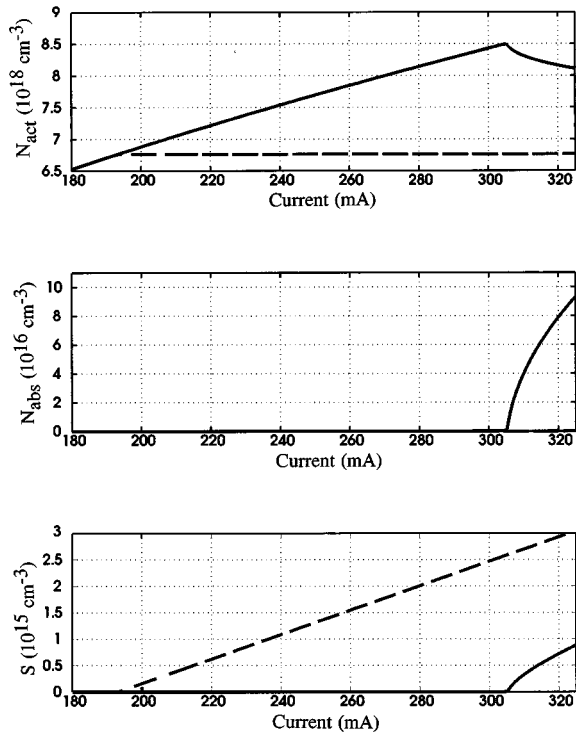


FIG. 1. Carrier and photon densities without absorber (dashed) and with absorber (full drawn).

$$g(N_{\text{act}}) = \gamma(N_{\text{act}} - N_{0\text{act}}), \quad \alpha(N_{\text{abs}}) = a \ln \left( \frac{N_2}{N_{\text{abs}} + N_1} \right). \quad (6)$$

Stability analysis can be applied to the set of Eqs. (1)–(3) by assuming a small variation of the three variables with an exponential time dependence. The resulting third degree characteristic equation can have either 3 real roots or one real and two conjugate complex. Complex roots indicate sinusoidal oscillations and when the real part of these roots is positive the oscillations will grow and lead to self-pulsations. A purely real positive root indicates that the laser can switch from one steady state to another and indicates bistability in the  $L$ – $I$  characteristic. The dc equations have been solved and the stability analysis has been carried out as a function of diode current for the following set of parameters

$$L = 300 \mu\text{m}, \quad d = 0.04 \mu\text{m}, \quad w = 50 \mu\text{m},$$

$$R_1 = R_2 = 0.3;$$

$$\alpha_{\text{int}} = 10 \text{ cm}^{-1}, \quad n_{\text{eff}} = 3.336, \quad \Gamma_{\text{act}} = 0.0951;$$

$$\gamma = 9.15 \times 10^{-17} \text{ cm}^{-1}, \quad N_{0\text{act}} = 1.0 \times 10^{18} \text{ cm}^{-3};$$

$$a = 2820 \text{ cm}^{-1}, \quad N_1 = 1.87 \times 10^{17} \text{ cm}^{-3},$$

$$N_2 = 1.12 \times 10^{18} \text{ cm}^{-3};$$

$$\tau_{\text{abs}} = 1.0 \times 10^{-9} \text{ s}, \quad B = 4.4 \times 10^{-11} \text{ cm}^3/\text{s},$$

$$\beta = 1 \times 10^{-5}.$$

The results are shown in Fig. 1. For the confinement factor of the absorbing layer  $\Gamma_{\text{abs}}$  two values have been chosen: 0 and 0.003, giving threshold currents of 193 and 306

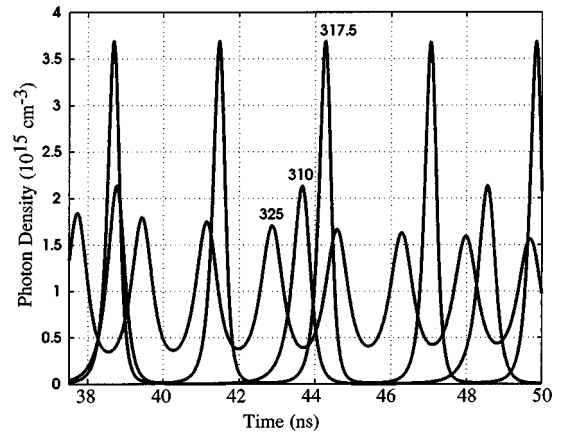


FIG. 2. Modeled self-pulsations: photon density against time. Parameter is device current in mA (50  $\mu\text{m}$  stripe width).

mA, respectively. In the latter case the complex roots have positive real parts in the current range of 306–322 mA.

If we now perform the full time integration of Eqs. (1)–(3) for this parameter set and a current in the unstable range self-oscillations are obtained as shown in Fig. 2. It was found that the attenuation of the absorber should be in the range of several thousand  $\text{cm}^{-1}$  and that its confinement factor should be around 0.3%. Optical simulations of the structure showed that this can be achieved at a thickness of 4 nm and an absorber-active layer distance of about 0.3  $\mu\text{m}$ .

Using OMVPE devices have been fabricated, all based on a standard AlGaAs laser design with a bulk active layer having an AlAs mole fraction of 13% and cladding layers with 50% AlAs. The operating wavelength is 785 nm. To avoid lateral mode effects the stripe width is 50  $\mu\text{m}$ .

For the saturable absorbing layer a pure GaAs quantum well was chosen. At a thickness of 4 nm this will have an absorption of about 7000  $\text{cm}^{-1}$ . The confinement factor was adjusted by varying the distance to the active layer from 0.1 to 0.5  $\mu\text{m}$ .

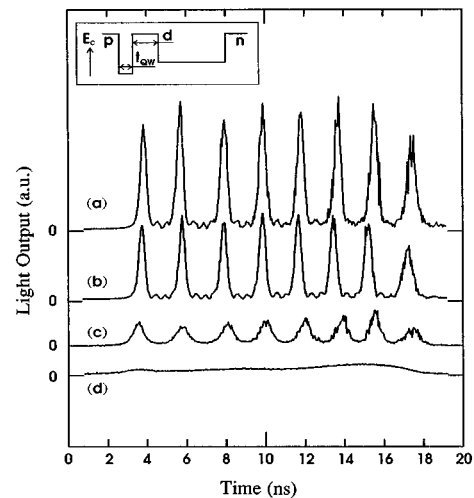


FIG. 3. Measured self-pulsations: light output against time at different values of the active layer-absorber distance. The current has been adjusted to obtain the same oscillation frequencies. Values for  $d$  ( $\mu\text{m}$ ) and  $I/I_{\text{th}} - 1$  (%) are: (a) 0.2, 5.7; (b) 0.3, 5.7; (c) 0.4, 4.6; (d) 0.5, 3.

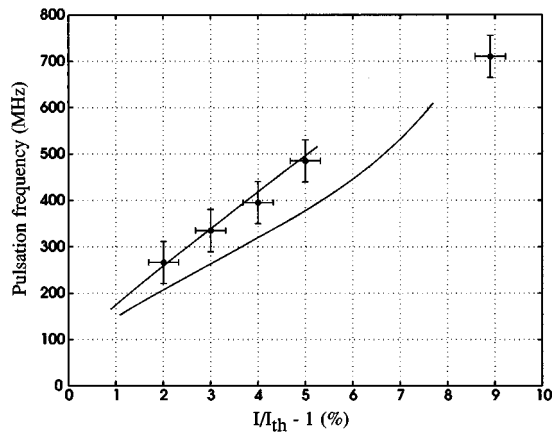


FIG. 4. Frequency of measured self-pulsations against device current. Full-drawn lines: model,  $\Gamma_{\text{abs}}=0.28\%$  (upper),  $0.32\%$  (lower). Points: experimental results,  $d=0.2 \mu\text{m}$ .

As expected from the simulations, the experimental threshold current increases with decreasing absorber-active layer distance. At a distance of  $0.1 \mu\text{m}$  however it decreases again since in this case the absorber is within a diffusion length from the active layer and experiences considerable minority carrier injection, reducing the absorption. In Fig. 3, the measured light output against time is shown for distances of  $0.2\text{--}0.5 \mu\text{m}$ . All except the  $0.5 \mu\text{m}$  device show sustained self-pulsations. In Fig. 4 the pulsation frequency is shown for an absorber-active layer distance of  $0.2 \mu\text{m}$ . As the figure shows the pulse repetition frequency increases with current, in reasonable agreement with the theoretical model.

It should be stressed that the experimental results are obtained in broad area devices, where any effects due to lateral mismatch between optical mode and current injection profiles are absent. These data demonstrate that controllable self-pulsation can be obtained by manipulation of the transverse layer structure only.

In conclusion, self-pulsations of broad area diode lasers with an extra layer functioning as a saturable absorber have been modeled and verified experimentally. The most important parameters appear to be the ratio of the active layer gain to the absorption of the absorber layer and the recovery time of the absorber.

Based on the model devices have been designed and tested. For the first time it has been demonstrated that it is possible to reproducibly induce stable pulsations in a frequency range of  $300\text{--}700 \text{ MHz}$ . The absorber must be placed in the  $p$ -doped cladding layer. Straightforward extension of this method towards shorter wavelength devices can be used to improve the feedback noise sensibility of visible light emitting laser diodes in high-density storage applications. Further investigation is necessary on the influence of stripe width, and of the doping of the absorber.

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