Scaling of the saturation energy in microcavity saturable absorber devices

David Massoubre,^{*} Jean-Louis Oudar, Julie Dion, and Jean-Christophe Harmand

*Laboratory for Photonics and Nanostructures - CNRS UPR 20,
Route de Nozay, 91460 Marcoussis, France*

Alexandre Shen, Jean Landreau, and Jean Decobert

Alcatel-Thales III-V Lab, Route de Nozay, 91460 Marcoussis, France

(Dated: February 7, 2006)

Abstract

Several all-optical switching devices based on quantum well microcavity structures have been studied, in view of their possible use for all-optical regeneration of telecommunication signals. Experiments and modelling show that the saturation energy is inversely proportional to a scaling factor describing the enhancement of the intracavity intensity at the Fabry-Perot resonance. As a result the saturation energy is approximately proportional to the number of quantum wells in the device, and can be kept small by a proper cavity design.

PACS numbers: Valid PACS appear here

^{*}Electronic address: david.massoubre@lpn.cnrs.fr

The next generation of optical telecommunication networks will need low cost, high performance devices. In this context all-optical devices with fast nonlinear optical response are attractive to combat cumulative transmission impairments by achieving a reshaping step [1]. Such gates, based on saturable absorbers (SA), have raised considerable interest due to their large non-linear optical effect, their compactness and their fully passive operating mode (no bias-voltage, no Peltier cooler), giving them a cost advantage [2]. Such devices have already been used as part of a 2 R regenerator (**R**eamplification and **R**eshaping steps) in 40 Gbit/s long-haul transmission lines and have allowed an important improvement of the propagation distance [3]. Multiple Quantum-Well (QW) saturable absorbers [4] typically have a rather long recovery time in the nanosecond range. So, to decrease their response time and make them compatible with high bit rate operation, capture and recombination centers must be introduced. This can be done during or after the crystal growth, via low-temperature growth molecular beam epitaxy [5], high-energy ion implantation [6] or Be- or Fe-doping [7, 8]. These methods of damage creation have been reported to provide recovery times as short as a few ps on InP-based semiconductor [6, 9]. Furthermore in order to amplify the non-linear response, SA are inserted inside an asymmetric Fabry–Perot microcavity and operate at resonance. This microcavity, designed to obtain a low reflectance at low incident energy, exalts the intracavity electromagnetic field and thus, combined with the excitonic absorption, enhances the non-linearity and decreases the effective saturation energy ($\mathbf{E}_s$). The combination of heavy-ion irradiation with a compact microcavity used at normal incidence has proved to be a practical solution for making efficient optical gates [2, 10].

In this Letter, we study experimentally the saturation energy of several quantum well SA microcavities with significantly varying cavity parameters, and relate the saturation energies to a scaling factor describing the enhancement of the intracavity intensity at the microcavity resonance. This microcavity enhancement factor β , defined as the ratio of the maximum intracavity intensity $\mathbf{I}_{max}$ to the incident intensity $\mathbf{I}_0$, is readily calculated from the usual procedure of Airy summation in a Fabry–Perot cavity [11]. For the simple case of normal incidence and operation at resonance it can be expressed as

$$\beta(\eta) = \frac{I_{max}}{I_0} = \frac{\left(1 + \sqrt{R_b e^{(-2\eta N \Gamma)}}\right)^2 (1 - R_f)}{\left(1 - \sqrt{R_f R_b e^{(-2\eta N \Gamma)}}\right)^2} \quad (1)$$

In this equation, $\mathbf{R}_f$ and $\mathbf{R}_b$ are respectively the front and back mirror reflectance, η is the single-pass absorption per QW, N the number of QW and Γ the longitudinal confinement factor of the microcavity [12]. Let us point out with some design considerations showing the conditions to meet for increasing the value of β . When differentiating the right-hand side of Eq. 1 with respect to $\mathbf{R}_f$, it is found that β is maximum if the impedance matching condition is achieved, i.e. if $R_f = R_b e^{(-2\eta N \Gamma)}$. In this case β becomes β_o :

$$\beta_o = \frac{(1 + \sqrt{R_b})^2}{(1 - R_b)} \quad (2)$$

Eq. 2 shows that β_o is much bigger than unity if $\mathbf{R}_f$ is close to 1. From the impedance matching condition, one sees that in order to get $\mathbf{R}_f$ close to 1, the back mirror reflectivity $\mathbf{R}_b$ must be even higher, and absorption must be low. Consequently, a solution to obtain a large β value is to design a microcavity structure with a low number of QW and with a high back mirror reflectance. We note that at impedance matching and with a $\mathbf{R}_f$ close to 1, β is proportional to the microcavity finesse f . As it will be described below, the device saturation energy $\mathbf{E}_s$ is experimentally determined at mid-saturation, i.e. when η is equal to $\eta_o/2$, where η_o is the unsaturated value of η . Therefore the expected scaling factor for $\mathbf{E}_s$ can be expressed as :

$$\beta_s = \frac{\Gamma}{2} \beta \left(\frac{\eta_o}{2} \right) \quad (3)$$

where a prefactor $\Gamma/2$ has been introduced to take into account the reduced light-matter interaction when all the QW are not located at the maximum intracavity intensity (in our studied structures, Γ is in the range from 1.45 to 1.95).

To investigate this potential method of reducing the saturation energy of SA microcavities, several optical gates with different numbers of QW have been fabricated. Their nonlinear optical responses have been measured, and compared to modelling results.

Five different structures A, B, C, D and E close to the impedance matching condition and similar to the ones reported elsewhere [13, 14], have been used for this study. They

consist of a SA layer made with QW comprised inside a Fabry–Perot microcavity. Table I summarizes the main characteristics of these switching gates. QW have been grown either by MBE (structure A) or by MOCVD. The QW are located at the antinodes of the intracavity intensity. After growth, the samples were irradiated by 12 MeV Ni^{6+} ions with an irradiation dose of $4 \cdot 10^{11} \text{ cm}^{-2}$ in order to reduce the carrier life time [6]. Pump and probe measurements have shown a recovery time of 3 ps. Then a thin Ag cap layer was deposited to form the back mirror after a top–down mounting onto a silicon host substrate. The InP substrate was ground to $\sim 75 \mu\text{m}$ and then etched down to a stop layer, subsequently removed by a selective etch solution. Finally a carefully controlled chemical etching of the InP phase layers led to a resonance at the desired wavelength. The front mirror, designed to obtain a low reflectance at low intensity, consists of either the simple InP surface, or a semiconductor Bragg mirror or a dielectric coating. Finally we obtained five microcavity structures close to the expected ones, as shown by the good agreement between the theoretical values of reflectance $\mathbf{R}$ at the cavity resonance and the experimental ones, measured with an optical spectrum analyser (OSA) (see column 5 in Tab. I). The slight differences are attributed to an imperfect optical quality of the mirrors, and also to the uncertainty on the materials optical properties. For each structure the value of β_s is given in column 6 of Tab. I.

The experimental setup used to measure the nonlinear behavior of these switching gates consists of a mode-locked fiber source producing 1 ps pulses at 19.44 MHz in the range from 1540 nm to 1560 nm. Its wavelength is adjusted to match the cavity resonance of each sample. The incident signal, after passing through a variable attenuator, is focused on the sample with a spot size of $4.1 \mu\text{m}$ (diameter at $1/e^2$ intensity), thanks to a microlensed fiber. The reflected output signal is detected and analyzed with a photodetector. This experimental set-up measures the reflectance transfer function, i.e. the microcavity reflectance $\mathbf{R}$ as a function of input energy $\mathbf{E}_{in}$. From the transfer function are deduced the optical contrast $\mathbf{C}$ which is defined as the ratio of the maximum reflectance $\mathbf{R}_{max}$ (passing state) to the minimum reflectance $\mathbf{R}_{min}$ (blocking state) and the optical insertion loss $\mathbf{IL}$ defined as $\mathbf{IL} = 10 \log(1/\mathbf{R}_{max})$.

The experimental results are summarized in Tab. II, and the plot $\mathbf{E}_s$ vs. β_s is displayed on Fig. 1. As expected the saturation energy is inversely proportional to β_s and decreases from $7.1 \mu\text{J}/\text{cm}^2$ to $1.1 \mu\text{J}/\text{cm}^2$ when going from structure A to structure D. This 6.5–fold decrease in saturation energy is well correlated to the corresponding increase of β_s , thanks

to a drastic reduction of the number of QW (28 to 3). Due to this higher enhancement factor, a lower input energy is required to saturate the QW and thus a lower saturation energy is observed.

Numerical simulations have also been carried out on the nonlinear response of these structures. The model includes the following physical aspects. The absorption coefficient η is assumed, as in a two-level system, to decrease linearly with carrier density n i.e. $\eta(n) = \eta_0(1 - n/n_t)$, where n_t is the carrier density at transparency. For an input pulse with gaussian temporal shape, the time evolution of n is computed, taking into account the carrier recombination time and the carrier-density-dependent microcavity enhancement factor β given by Eq. 1. This allows to compute the time evolution of the microcavity reflectance, and of the local reflected intensity $I(r, t)$. A simple time domain integration provides the reflected fluence for each incident fluence. Furthermore, as the incident beam has a gaussian transverse intensity profile, the nonlinear response is inherently different at the center of the beam and at the edges. The effect of this non-uniform spatial intensity profile is taken into account using the classical approach described in ref. [15].

The calculations were performed with the following parameters. R_b , R_f and N were the values indicated in Tab. I, Γ was calculated from the intracavity intensity pattern, and η_0 was set at 0.77 % per QW. The pulse duration was set to 1.2 ps, and the carrier density at transparency n_t was set to $2.10^{12} \text{ cm}^{-2}$. Numerical results for some structures are given on Fig. 2 with the corresponding experimental results displayed for comparison. On Fig. 2 the transfer functions have been normalized between 0 and 1 for the simplicity of comparison. Experimental and numerical results are in very good agreement, showing a 8 dB decrease of the saturation energy when the number of QW is reduced from 28 to 3. This improvement is accompanied by a decrease in R_{max} , because the back mirror loss takes more importance at higher finesse (*cf.* Tab. II). The use of a back mirror reflectance very close to 1 would increase this maximum device reflectivity (ideally up to 1 in the case of no mirror loss), with some reduction (by typically 40 to 50%) of E_s as an added benefit.

Comparing Table II and Fig. 2, we note that the saturation energy of a device is smaller, by about a factor of 8, than the pulse energy required to switch the device midway between R_{min} and R_{max} , thus increasing the apparent switching energy. This is due to the combination of several effects, (1) transient effects specific to the present self-saturation configuration - only the trailing edge of the pulse is “switched on” -, (2) nonuniform intensity - only the

spot central region is “switched on” -, and (3) nonlinear dependence of the device reflectance with absorption η - when η is bleached by 50 %, R is smaller than $(R_{min} + R_{max})/2$.

Finally the scaling factor β can be further increased, by still decreasing the number of quantum wells in the microcavity. For instance a microcavity with a single QW, $R_f=99.5\%$ and $R_b=95\%$ would have $\beta_s=160$, and a saturation energy of $0.25\text{ }\mu\text{J}/\text{cm}^2$, corresponding to 15 fJ with the same spot size as in our experiments.

In summary, nonlinear optical measurements have been performed on saturable absorber microcavities, suitably designed and fabricated with significantly varying cavity parameters. Numerical and experimental results show that the saturation energy decreases with the number of QW, because of a higher microcavity enhancement factor. A saturation energy as low as $1.1\text{ }\mu\text{J}.\text{cm}^{-2}$ has been measured for a structure with only 3 QW. Such low saturation energy devices have potential applications in 2 R regenerated transmission lines.

Acknowledgments

The authors gratefully acknowledge the help of S. Sauvage and H. Bernas from the University of Orsay, France, for the ion-irradiation. We would also like to thank Dr. B. Thédrez from Alcatel-Thales III-V Lab for helpful discussion. This work was partially supported by the French Telecom Research Network (RNRT-ASTERIX project), the Conseil Général de l'Essonne and the ministère de l'industrie.

-
- [1] O. Leclerc, B. Lavigne, E. Balmeffre, P. Brindel, L. Pierre, D. Rouvillain, and F. Seguneau, *J. of Lighthwave Technol.* **21**, 2779 (2003).
- [2] J. Mangeney, G. Aubin, J. L. Oudar, J. C. Harmand, G. Patriarche, H. Choumane, N. Stelmakh, and J. M. Lourtioz, *Electron. Lett.* **36**, 1486 (2000).
- [3] D. Rouvillain, P. Brindel, F. Seguneau, L. Pierre, O. Leclerc, H. Choumane, G. Aubin, and J. L. Oudar, *Electron. Lett.* **38**, 1113 (2002).
- [4] D. A. B. Miller, D. S. Chemla, D. J. Eilenberger, P. W. Smith, A. C. Gossars, and W. T. Tsang, *Appl. Phys. Lett.* **41**, 679 (1982).
- [5] R. Takahashi, Y. Kawamura, T. Kagawa, and H. Iwamura, *Appl. Phys. Lett.* **65**, 1790 (1994).
- [6] E. L. Delpon, J. L. Oudar, N. Bouche, R. Raj, A. Shen, N. Stelmakh, and J. M. Lourtioz, *Appl. Phys. Lett.* **72**, 759 (1998).
- [7] L. Qian, S. D. Benjamin, P. W. E. Smith, B. J. Robinson, and D. A. Thompson, *Appl. Phys. Lett.* **71**, 1513 (1997).
- [8] M. Guezo, S. Loualiche, J. Even, A. L. Corre, O. Dehaese, Y. Pellan, and A. Marceaux, *Journal of Applied Physics* **94**, 2355 (2003).
- [9] M. Pantouvaki, R. Gwilliam, E. P. Burr, A. B. Krysa, J. S. Roberts, and A. Seeds, in *IPRM'2003* (Santa Barbara, USA, 2003).
- [10] M. Pantouvaki, M. J. Fice, R. Feced, E. P. Burr, R. Gwilliam, A. B. Krysa, J. S. Roberts, and A. J. Seeds, *IEEE Phot. Tech. Lett.* **16**, 617 (2004).
- [11] M. Born and E. Wolf, *Principles of Optics*, 6th edition, Pergamon Press, pp. 325–326 (1980).
- [12] S. Corzine, R. S. Geels, J. Scott, R. Yan, and L. A. Coldren, *IEEE J. Quantum Electron.* **25**, 1513 (1989).
- [13] J. Mangeney, S. Barr, G. Aubin, J. L. Oudar, and O. Leclerc, *Electron. Lett.* **36**, 1725 (2000).
- [14] D. Massoubre, J. L. Oudar, G. Aubin, J. Dion, A. Shen, J. Decobert, N. Lagay, A. O'Hare, Z. Belfqih, M. Gay, L. Bramerie, S. Seve, E. Lecren, and J. C. Simon, in *CLEO 2005* (Baltimore, USA, 2005).
- [15] P. Kolodner, H. S. Kwok, Jerry, G. Black, and E. Yablonovitch, *Opt. Lett.* **4**, 38 (1979).

Tables

TABLE I: Main characteristics of the microcavities used for this study. $\mathbf{R}_b$ and $\mathbf{R}_f$ are the back and front mirror reflectances respectively, $\mathbf{R}$ is the microcavity reflectance at low incident power, with the theoretical value in brackets. $\mathbf{N}$ is the number of QW and β_s is calculated from Eq. 3. Ag is a silver layer.

structure	active layer ($\mathbf{N} \times \text{QWs}$)	back mirror ($\mathbf{R}_b$)	front mirror ($\mathbf{R}_f$)	$\mathbf{R}$ (<i>theo</i>)	β_s
A	28 $\times$ InGaAs/InAlAs	Ag (94 %)	InP/air (27 %)	6.0 % (6.3 %)	5.9
B	9 $\times$ InGaAs/InP	Ag (94 %)	6 $\times$ InGaAsP/InP (61 %)	5.0 % (7.6 %)	13.5
C	7 $\times$ InGaAs/InAlAs	Ag (94 %)	6 $\times$ InGaAlAs/InP (68 %)	2.3 % (3.2 %)	17.8
D	3 $\times$ InGaAlAs/InGaAlAs	Ag (94 %)	2 $\times$ TiO ₂ /SiO ₂ (80 %)	9.3 % (3.8 %)	31.8
E	4 $\times$ InGaAlAs/InGaAlAs	Ag + 4.5 $\times$ InGaAlAs/InP (97.5 %)	2 $\times$ TiO ₂ /SiO ₂ (80 %)	4.6 % (5.1 %)	35.4

TABLE II: Experimental and numerical results. N is the number of QW, C is the optical contrast in dB, IL is the optical insertion loss in dB, E_s and E_{th} are the experimental and theoretical saturation energies respectively (in $\mu\text{J}/\text{cm}^2$).

structure	N	C	IL	E_s	E_{th}
A	28	3.2	2.1	6.3	7.1
B	9	9.7	2.0	2.7	2.7
C	7	8.9	2.4	2.0	2.3
D	3	7.0	3.8	1.1	1.4
E	4	5.1	1.9	1.0	1.1

Figures

FIG. 1: Experimental and numerical saturation energies (E_s) versus the mid-saturation exaltation factor (β_s). The experimental data fitting curve is proportional to $1/\beta_s$.

FIG. 2: Comparison of experimental and numerical transfer functions for structures A, B and D. The transfer functions are normalized between 0 and 1 for the simplicity of comparison.