Controlling a laser output through an active saturable absorber

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Using the modified Statz - De Mars equations to describe a two laser optical system, it is shown how a saturable absorber can be made into an active control device when an external Electro Optic Modulator modulated low-intensity laser pumps directly into a saturable absorber inside a dye laser cavity. The direct modulation enables to control when and how the pulse train coming from the saturable absorber is released. The results here presented show that the pulse characteristics such as width, intensity and pulse frequency coming from the dye laser cavity, depend on the absorber characteristics and the modulation frequency.

Keywords: Laser; optical resonator; laser dynamics.

Usando las ecuaciones de Statz - De Mars modificadas para describir un sistema óptico de dos láseres se muestra como un absorbedor saturable puede convertirse en un dispositivo de control activo cuando una señal externa de baja intensidad, modulada por un Modulador Electro Óptico, es inyectada directamente en él cuando se encuentra dentro de una cavidad de láser de colorante. La modulación directa permite controlar cuándo y cómo se libera el tren de pulsos que proviene del absorbedor saturable. Los resultados aquí presentados muestran que las características de intensidad, anchura y frecuencia de pulso proveniente de la cavidad láser de colorante dependen de las características físicas del absorbedor y de la frecuencia de modulación aplicada al láser de control.

Descriptores: Láser; resonadores ópticos; dinámica de láseres.

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1. Introduction

The Statz - De Mars equations' system has been broadly used to model laser systems for almost 50 years. Originally designed to describe the oscillations in a maser [1], it has since undergone many modifications to describe more complex systems. Particularly in this work, terms that take into account on one hand a saturable absorber (SA) and on the other a control beam are added to these equations.

Fluorescent dye lasers have been widely used as an amplifier media for incident laser signal beams at several wavelengths [2,3]. Moreover it has also been shown [4] that the steady-state transmission of a pump beam through a laser amplifier can be controlled by the intensity of a signal beam from an auxiliary laser, suggesting that the signal laser beam can be used as an optical switch. While the authors [4] used a dye cell as an active media and switching device, in the present paper a dye laser beam will be used as a signal beam and a SA controlled by an external modulated beam (control beam) will replace the dye cell, in this way the saturable absorber is in fact turned into an active device.

A SA is a non-linear optical component with a certain optical loss, which is reduced at high optical intensities [5]. Depending on the parameters of the SA they are usually used for passive mode-locking and Q-switching [6]. It is well known that continuous wave dye lasers with SAs provide short pulses due to self-stabilization of the pulse shaping process [7]. A SA inserted into a laser cavity increases the nonlinearity of such system and enriches the laser operation dynamics [8]. Mode-locking laser dynamics has been an important study subject [9], traditionally mode-locking is actively obtained with an optical modulator inside the cavity or passively with a SA. In this work, we believe for the first time, the two are combined by reallocating the optical modulator outside the cavity and injecting its signal into an intracavity SA; the modulated signal comes from a low-intensity continuous wave laser.

While, the important characteristics of a SA are: modulation depth (maximum possible change in optical loss), unsaturable losses (unwanted losses which cannot be saturated), recovery time, saturation fluence, saturation energy and damage threshold (given in terms of intensity) [5], the modified Statz - De Mars equations require only to take into account for the SA, its geometry, its active absorbent nuclei density and its relaxation time [10].

For a long time SAs have been considered passive devices [11-13]. As shown in Ref. 15 a dye cell with an external signal beam may be used as a switching device. If now an external modulated low intensity beam is injected directly into the SA, the optical losses and the saturation fluence are modified according to the frequency injected transforming the device into an active one. Thus the saturable absorber becomes an important control tool.

This work presents a numerical simulation of a dye laser output with an intracavity SA behaving as an active device due to an external modulation. The simulation considers an auxiliary beam coming out of the low-energy CW laser and modulated by an electro-optical modulator (EOM) that is injected transversally into the SA; so that the control of the main laser is obtained through the absorber. The dye laser is described by the Statz - De Mars equations, these will be modified to take into account both the SA and an external modulation. The parameters where chosen for a typical dye laser [16], while we played with the modulation frequency and the SA's absorption parameter. The results will show that with such device the laser output goes from a continuous wave regime to a narrow train of high peaks with constant amplitude (comb like) passing through a modulation frequency window where the overall shape of the wave is very smooth even though it may present a collection of undamped undulations at different pulse locations depending on the working parameters.

2. Theoretical model

Using the Statz-De Mars equations for a three level laser with a SA [10] the derivatives of the emitted-photon density S, the population in the active medium N, and the population inversion in the SA k_a, are given as:

$$\frac{dS}{dt} = \Gamma v \sigma NS - \Gamma v \frac{l_a}{l} k_a S - \frac{1}{T} S \tag{1}$$

$$\frac{dN}{dt} = -\beta \frac{\sigma}{\hbar w} NS + \frac{N_0 - N}{\tau} \tag{2}$$

$$\frac{dk_a}{dt} = -\frac{2\sigma_a k_a S}{\hbar w} + \frac{k_{0a} - k_a}{\tau_a} \tag{3}$$

where the parameters

$$\Gamma = (l/\nu)/(l/\nu + l_a/\nu_a + [L/c - (l + l_a)]/c),$$

$$T = \{\Gamma\nu[\eta_1 + (l_a/l)\eta_{1a} + \eta_a]\}^{-1},$$

ν, and σ stand for cavity-filling coefficient, photon cavity life-time, optical frequency and active medium cross-section respectively, β is an integer used to describe the variation of the difference in population inversion between the transition levels during a photon emission, l is the cavity length, while l_a is the SA length, k_{0a} is the k_a steady-state value, σ_a represents the SA cross-section, N_0 is the total initial population in the active medium, τ and τ_a stand for relaxation time in the active medium and the SA respectively,η, η_a represent, respectively, the total absorption coefficient for the active medium and for the SA, finally, $\hbar w$ is the product between the Planck's constant and the optical frequency, representing the photon energy.

In order to simplify the manipulation of this equations system it is a standard procedure [10,14] to transform it into an adimensional one, to do so the following parameters are defined as t'=t/τ, G= τ/T, $\delta = \tau/\tau_a$, ρ=2$\sigma_a/\beta\sigma$, $\alpha = \Gamma\nu\sigma$TN, α_a=-$\Gamma\nu$Tk$_{0a}(l_a/l)$, and the equation variables as: n(t')=$\Gamma\nu\sigma$TN(t'), n_a(t')=-$\Gamma\nu$(l$_a$/l)Tk$_a(t')$ and m(t')=$\beta\sigma\tau$S(t')/$\hbar w$.

The adimensional Statz - De Mars equations system can be written as:

$$\frac{dm}{dt} = Gm(n + n_a - 1) \tag{4}$$

$$\frac{dn}{dt} = \alpha - n(m + 1) \tag{5}$$

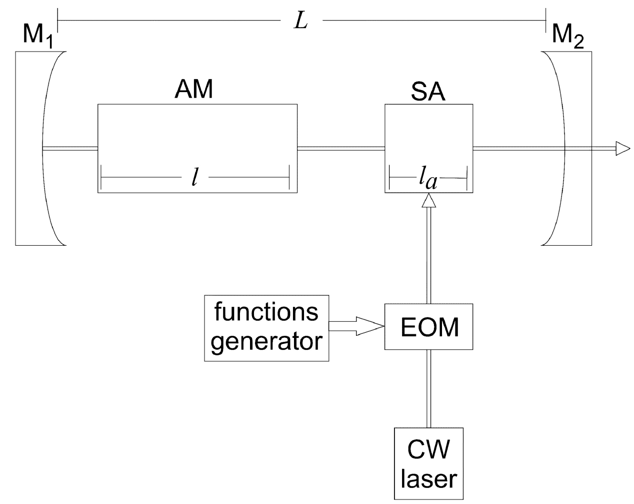

FIGURE 1. Laser scheme with an active intracavity saturable absorber.

$$\frac{dn_a}{dt} = \delta\alpha_a - n_a(\rho m + \delta) \tag{6}$$

On the other hand it has already been demonstrated [15,16] that an external signal injected directly into the cavity can be used as an optical switch to modify the shape of the output signal, *i.e.* an optical system formed by a high-power laser and a low-power control one. If these results are generalized for a laser with a SA and a modulated control signal is injected into the SA one obtains an *active* device; the laser output depends directly of the SA behavior. As soon as a modulated signal is injected into the absorber the output signal shows a periodic behavior, its period is clearly proportional to the control signal one. In this work the Statz – De Mars equations will be modified to numerically describe the behavior of a laser made up by a dye active medium (AM), two mirrors (total reflexion, M1, and semitransparent mirror, M2) and an intracavity saturable absorber (SA) coupled with a low-power continuous wave (CW) laser through an Electro-Optical Modulator (EOM) as shown in Fig. 1.

The modified adimensional Statz – De Mars equations that take into account the modulated control signal, *cos* (ωt) into the system stand as follows:

$$\frac{dm}{dt} = Gm(n + n_a - 1) \tag{7}$$

$$\frac{dn}{dt} = \alpha - n(m + 1) \tag{8}$$

$$\frac{dn_a}{dt} = \delta\alpha_a(\frac{1 + \cos(\omega t)}{2}) - n_a(\rho m + \delta) \tag{9}$$

where ω stands for the modulation frequency applied to the EOM.

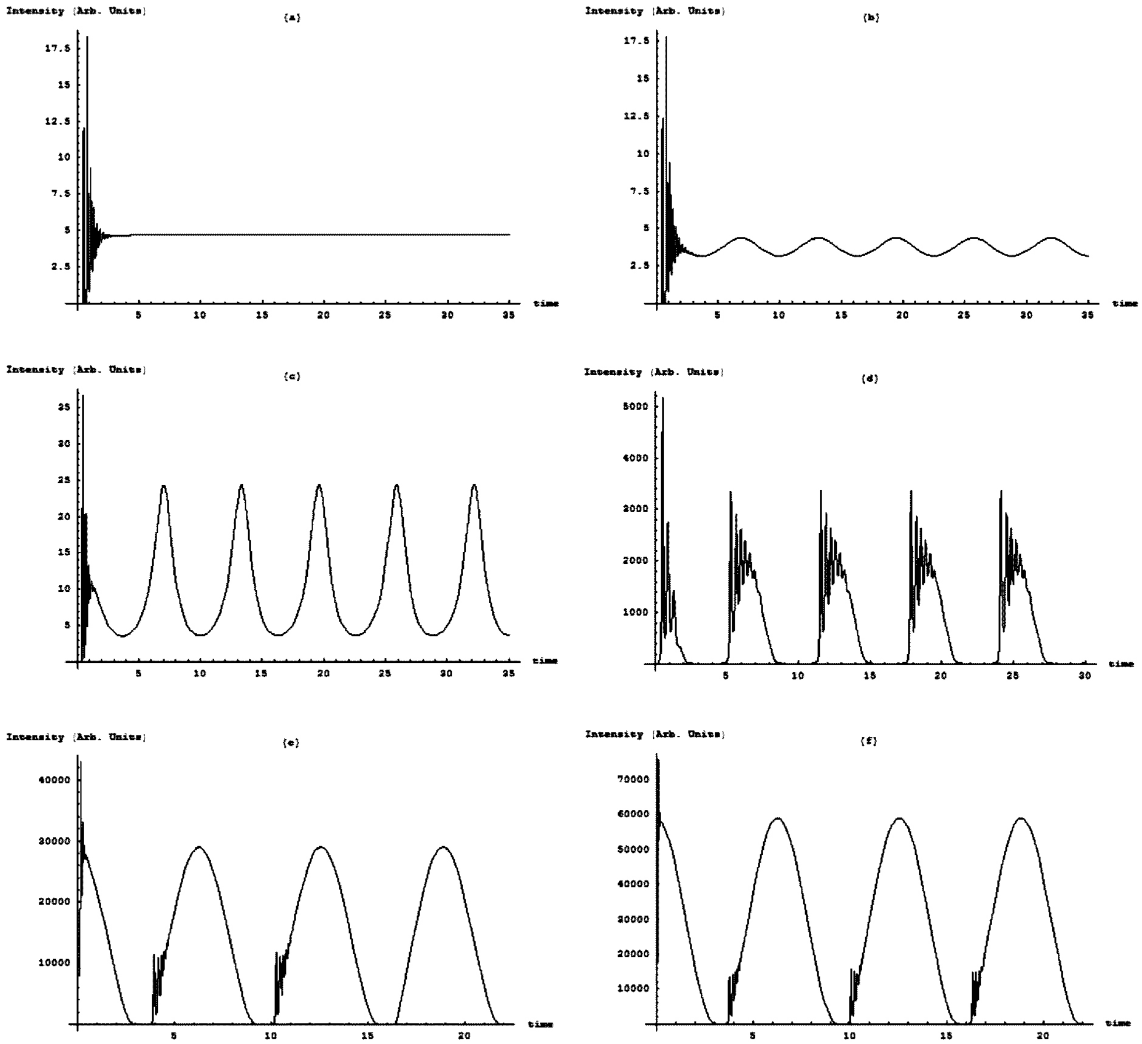

FIGURE 2. Dye laser output intensity. a) without modulation; b, c, d, e, f) with modulation and an α_a of 0.3, 1, 3, 30 and 60 respectively.

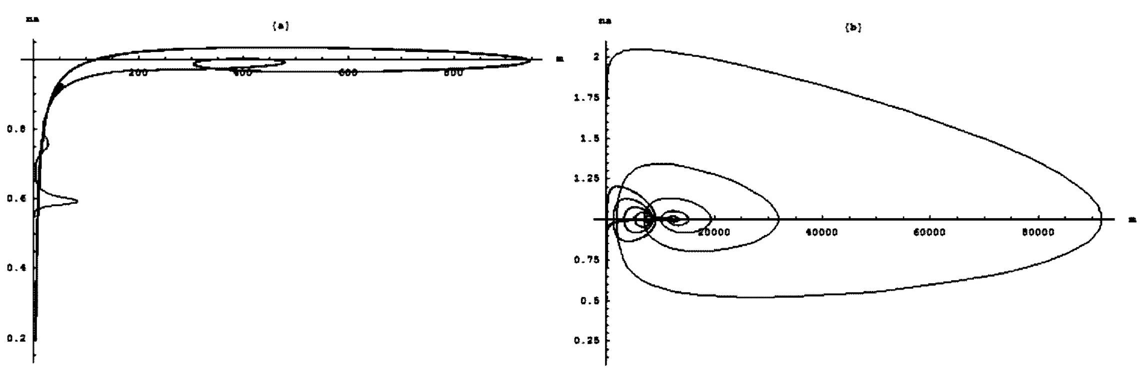

FIGURE 3. Phase diagram m vs n_a. a) with α_a= 1.4 b)with α_a= 30.

3. Numerical results

To find the solutions of the Eqs. (7-9) a Mathematica code was build using the typical [16] Statz - De Mars parameters for a Dye laser G= 200, α= 4, δ= 1, ρ = 0.001 and as initial values m_0= 0.25, n_0= 0 and n_{a0}= 0.152. It was observed that the system actually tends to a fixed point in a short computational time and to a periodic behavior when the external modulation is on. With a fixed ω the only parameter we can actually play with is α_a, a measure of the active centers absorbent density. Since the geometrical parameters that are involved in the definition of α_a will be fixed, the parameter

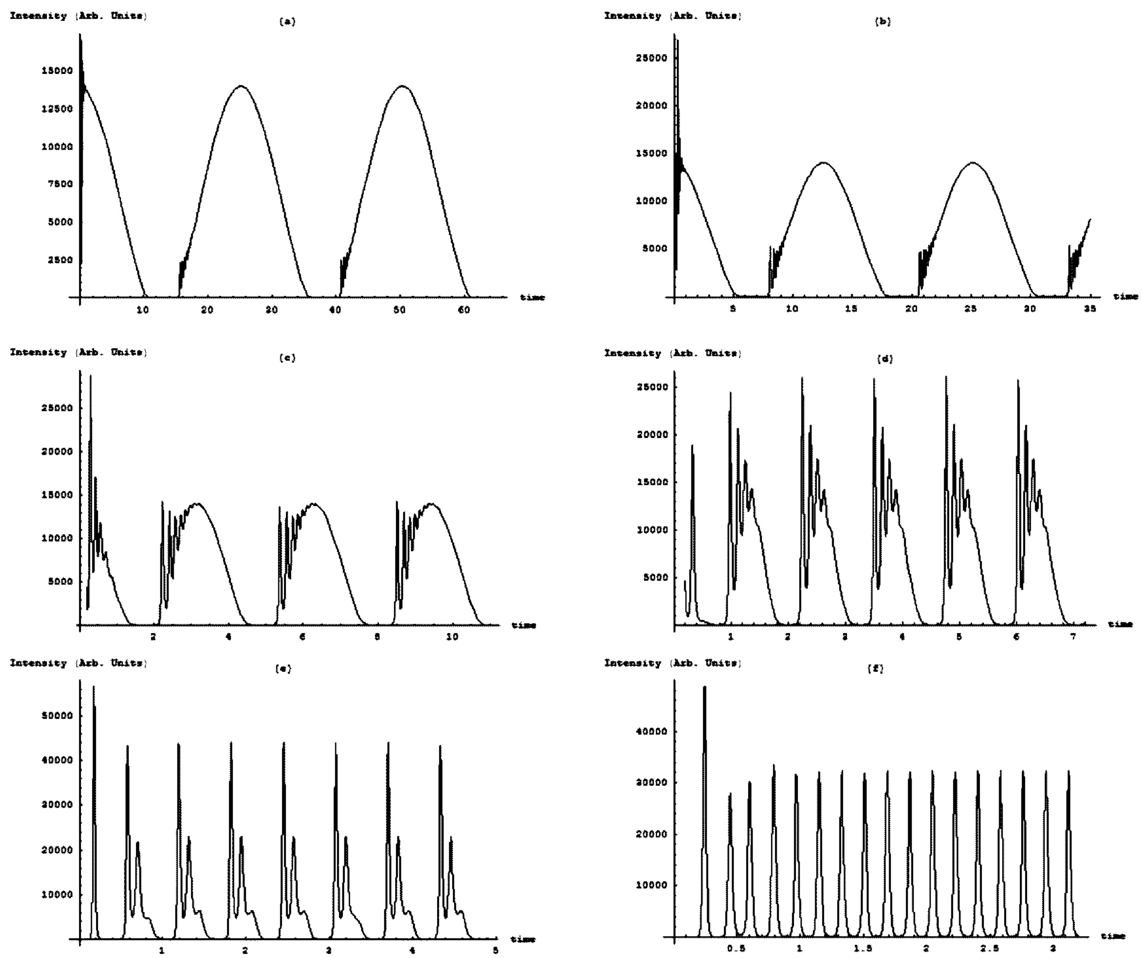

FIGURE 4. Pulse shape at α_a= 15 with frequencies ω. a) 1/4, b) 1/2, c) 2, d) 5, e)10, f) 35.

α_a will be identified as absorption ratio and therefore will depend on the chosen SA (in a dye SA its dependence vary according to the dye concentration), the values for this numerical experiment were chosen in the practical range (0.3, 63). When the Statz - De Mars equations were solved without modulation, m reached a fixed point in few iterations (Fig. 2a), as soon as the modulation is injected into the absorber a periodic pulse train begins to appear (Fig. 2b, c, d, e, f) with α_a as small as 0.3, as α_a is increased the maximum intensity reached increases and a region of different frequencies coexistence begins to appear at a certain location in the pulse, this location depends on the absorption ratio.

It can be observed from Fig. 2 that the laser output tends to a fixed point when the SA is in passive configuration, *i.e.* without external modulation; as soon as the SA is turned into an active device, different packages of pulses are obtained depending on the SA's absorption ratio (α_a), the bigger the concentration the higher the reached intensity. The laser output, in this case, goes from a continuous wave regime to a high-intensity peaks train passing, through an undamped undulations window moving across the pulse's body.

When the absorption ratio is larger than a threshold that depends on the modulation frequency, the phase diagram between m and n_a exhibits instead of one, two critical points, as shown in Fig. 3. When the frequency is 1 this phenomenon appears for an α_a value near 1.4. If α_a= 30 the two critical points in the phase diagrams are far enough from one another to emphasize the phenomenon (Fig. 3b).

The laser output signal is very important, if the geometrical variables are fixed the only variables that have a great impact on the laser dynamics are α_a and ω. Therefore, a comprehensive study on the output signal in terms of ω was done for an α_a= 15, the value was chosen first of all because the undamped undulations are obvious for small ω and are nowhere near the maximum intensity reached by the laser output; its behavior is representative of what happens at any frequency even if there are some differences in detail. Figure 4 shows how the signal frequency increases following the change in the modulation frequency. As the frequency rises, a threshold is obtained where the narrow pulse train is reached, its value is closely related with α_a, a change in the absorption ratio only moves the undamped undulations window; the window is shifted towards the right (both thresholds get larger) as α_a is increased. The second threshold corresponds to the appearance of a narrow pulse train, when α_a= 15 the narrow high intensity pulse train is obtained at around ω=35.

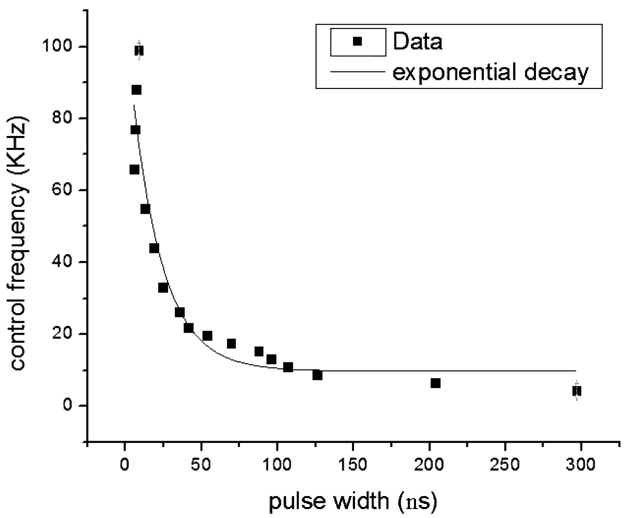

FIGURE 5. Pulse width against control frequency. It is shown how the pulses width become narrower as the control frequency is increased.

When a SA is used in a conventional manner, once the SA operational parameters are fixed, the laser repetition rate and the peak intensity achievable are also fixed due to the SA properties. However, in the proposed scheme these properties can be externally controlled by modifying the injected power frequency, given as a result, a wider range of pulses generation. This is the main advantage of our proposal.

The dependence between the output pulse width and the modulation frequency, shown in Fig. 5, is clearly a very good approximation to an exponential decay. It must be noted that the modulation frequency ω enters the equation as an integer multiple of the laser relaxation frequency w, so that the pulse duration is calculated from the relaxation time. From the above considerations one can observe a width lower limit around 19 ns achieved approximately at 80 KHz, which is 35 times the relaxation frequency.

4. Conclusions

This paper effectively shows how a saturable absorber can be made in to an *active* device to control the output of a Dye laser. The insertion of a modulated signal directly into the saturable absorber modifies the continuous output driving it into a periodic one. The larger the α_a the higher the laser intensity obtained, and the more comb-like it becomes. For a given α_a there are two important thresholds: the modulation frequency where the undamped undulations appear and the one where they disappear, as the absorption ratio is increased, the undulations window is shifted towards higher frequencies. For a given α_a, as the modulation frequency is increased, the output signal changes from a smooth periodic function to a clear comb-like pulse train whose width decreases exponentially, thus the saturable absorber is behaving as an *active* device.

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