Improved Bandwidth in VCSEL with AC Modulated Holding Beam

Sahar Ahmadipanah[a], Reza Kheradmand[a], and Franco Prati[b]

[a]Photonics group, Research Institute for Applied Physics and Astronomy, University of Tabriz, Tabriz, Iran.
[b]Department of Science and High Technology, University of Insubria,Via Vallegio11, Como, Italy.

Corresponding Author: r_kheradmand@tabrizu.ac.ir

ABSTRACT— A modulated holding beam shining a VCSEL above threshold can improve modulation bandwidth by adjusting the semiconductor laser's relaxation oscillation frequency. The improved modulation characteristics are accompanied by reduced damping rate. By choosing correct parameters, dynamical behavior of system and cavity solitons is changed.

KEYWORDS: Cavity Soliton, Holding beam, Modulation, Bandwidth, Damping rate, Relaxation oscillation frequency.

I. INTRODUCTION

Holding beam is an external coherent beam with uniform intensity driving the vertical cavity surface emitting laser (VCSEL). More specifically, it relates to an essential element for generating cavity solitons and cavity acts just as a modulator or intensity amplifier for VCSEL. Some characteristics of such an external coherent beam are regenerating the energy of cavity, compensating the losses, operating as a control parameter and determining the reference phase of intra cavity field. Local excitation, in-phase with the holding beam and π-phase shifted, is used to writing and erasing the cavity solitons for externally driven VCSELs respectively [1-3]. Holding beam also defines the fixed phase all across the transverse section of the device. For amplifying systems in which holding beam is always on, motion of cavity solitons can be induced either by a phase or intensity mask on the holding beam(injected field) [4]. Theoretical and experimental studies for cavity solitons (CSs) existence, in vertical cavity semiconductor amplifier and optical control of them are widely exhibited [5-6]. Moreover, a spatial modulation of the holding beam intensity has been introduced [7]. A need remains for a process that modulates injected field temporally. The paper is intended to satisfy temporally modulation on holding beam. During this new type of modulation, calculation of relaxation oscillation (RO) frequency is necessary. The relaxation oscillation frequency provides an indication of modulation speed in semiconductor lasers [8-10]. A semiconductor laser exhibits damped relaxation oscillations because of a time dependent energy exchange between laser field and carrier population. RO frequency for free-running semiconductor lasers typically ranges 1-20 GHz [11-12]. An interesting discovery is that the RO frequency of a semiconductor laser would appreciably increase with injection locking [8,13].

Improved modulation characteristics are accompanied by resonance condition, which is easily obtained when modulation frequency is RO frequency of system. The invention relates generally to a process for large responses in resonance modulated semiconductor laser. The modulation bandwidth of strongly injection-locked semiconductor lasers can significantly improved compared to free-running electrical modulation [11-12]. The modulation bandwidth can be 2–3 times of the free-running value. This is very attractive since it may allow achieving large modulation bandwidths with conventional semiconductor lasers at room temperature, avoiding the use of advanced devices and the need for complicated fabrication techniques. Furthermore, injection locking in semiconductor lasers is an attractive method to ensure single mode operation [13], reduce the line width of free-running laser [14], and eliminate mode partition noise [15], mode hopping, and frequency chirp from modulated lasers [16]. The injection-locking technique may also prevent spurious feedback effects that are random and difficult to avoid and can strongly disturb the behavior of the laser. A promising method to generate microwave signals and synchronize one or more free-running lasers to a pump laser is injection locking [17].

Semiconductor laser exhibits damped relaxation oscillations because of a time dependent energy exchange between laser field and carrier population. Right after the laser turns on, the amplitude varies for a while and then gets stabilized to a constant. Frequency before the laser goes to stabilized manner is called relaxation oscillation (RO) frequency. For free running semiconductor laser, RO frequency is of the order of $\sqrt{\gamma_p \gamma_c}$, where γ_p and γ_c are the decay rates of photons and carriers, respectively. When the parameters are enhanced by an external optical injection, the RO frequency would show an increased feature.

The cavity soliton laser combines the low frequency of bistable systems in general and of CSs in particular, with the enhanced RO frequency of injection locked semiconductor lasers. We show that the two combined effects lead to a modulation bandwidth larger than 100 GHz when the modulation of the external beam is processed by cavity soliton (CS).

In this paper we consider a broad area VCSEL above threshold driven by an external coherent beam. In the following system, holding beam is temporally modulated. By first measuring the RO frequency of system and study about system behavior and modulation characteristics, we finally show modulation effects on bandwidth.

The paper is organized as follows: in Section II considered model is introduced; Section III is devoted to simulation results and discussions and finally Section V allocated by summary of findings and conclusion.

II. MODEL

We consider a broad area VCSEL above threshold driven by an external coherent beam, in which cavity solitons (CSs) are demonstrated [1]. Such a system combines the low frequency amplification properties of bistable systems in general and of CSs in particular, with the enhanced RO frequency of injection locked semiconductor lasers. Following full set of effective Maxwell-Bloch equations can be suitably describe an optically injected broad area VCSEL.

$$\dot{E} = \sigma\left[P + E_i - (1 + i\theta)E + i\nabla_\perp{}^2 E\right] \tag{1}$$

$$\dot{D} = -b\left[\frac{1}{2}\left(E^* P + P^* E\right) + D - J - d\nabla^2 D\right] \tag{2}$$

$$\dot{P} = \Gamma\left(1 + i\Delta\right)\left[\left(1 - i\alpha\right)\left(1 - \beta D\right)DE - P\right] \tag{3}$$

where *E* and *P* are slowly varying envelops of electric field and effective macroscopic polarization respectively. ∇^2 is the Laplacian operator. Dot and star sign mean temporal behavior and complex conjugate of variables, respectively. E_i represents the injected field. *J* is the parameter related to the pump current. Parameter α referred to the line-width enhancement factor and γ related to population decay. The parameter *D* is population variable proportional to the excess of carries with respect to transparency. The decay rates define as $\sigma = \tau_d / \tau_p$, $b = \tau_d / \tau_c$, where τ_p, τ_c, and τ_d are the photon lifetime, carrier recombination time and dephasing rate of microscopic dipole respectively. Time is scaled to dephasing rate τ_d of microscopic dipole. Detuning $\theta = \frac{\omega_c - \omega_0}{\kappa}$ represents the frequency difference between cavity longitudinal mode and of the injected field scaled to cavity linewidth κ. Parameter $\beta = 0.125$, referred to carrier and gain quantity dependency. In this regime relation between carriers and gain are considered nonlinear (for more details see [14]). By introducing the quadratic fitting of the gain curve in the equations, the model will be more realistic with some unique features [1]. However, we consider the specific case of small pump current, *J*, and sufficiently high injected amplitude, E_I, to ensure that the VCSEL operates beyond the injection locking point. The lower branch of the homogenous solution, which constitutes the background for CS, is stable [1].

All variables and parameters are dimensionless. Time is scaled to the carrier lifetime (assumed to be 1ns) and frequencies to its inverse (1 GHz). The equations include diffraction an carrier diffusion through the Laplacian terms, where the transverse coordinates are scaled to the diffraction length so that *d* is the squared ratio of diffusion to diffraction length. In this paper $d = 0.05$.

Above equations assume VCSEL with external injection, in which electric field is a homogeneous uniform DC like beam. A dynamical equation for the macroscopic polarization *P* is necessary to avoid unphysical short wave length instabilities below the injection locking point. Yet, as long as one is interested just in the homogeneous stationary solution and in the stationary CSs above the locking point, the equations:

$$\dot{E} = \sigma\left[(1-i\alpha)D(1-\beta D)E + E_i - (1+i\theta)E + i\nabla_\perp{}^2 E\right] \tag{4}$$

$$\dot{D} = -b\left[\frac{1}{2}\left(D(1-\beta D)|E|^2\right) + D - J - d\nabla^2 D\right] \tag{5}$$

Which are obtained with a standard adiabatic elimination of *P*, are sufficient.

Nonlinear dynamical equations (1)-(3) which are differential equations with spatial and temporal derivatives, are integrated by split step based on Fast Fourier transform (FFT) with periodic boundary condition. Dimension is selected large enough for simulation, so that variabale's value on boundary be equal with theier limit of infinit values. This method, which is called pseudo spectral method, shows the dynamical state of each points on emitting surface of VCSEL with time.In this method, by supposing initial value for variables of system (*E*, *P*, *D*) real space is brake, which in two dimensions is equal to 2×2 matrix. All variables of system will have defined values in matrix elements. In Split-Step, method temporal and spatial parts of equations are separated and solved independently.

In this paper, we apply an AC modulation to the injected field in the form:

$$|E_i|^2 = |E_0|^2 + |E_m|^2 \sin^2(2\pi\nu t) \tag{6}$$

where $|E_i|^2$ is injected field intensity, $|E_0|^2$ is initial homogeneous holding beam value and $|E_m|^2$ is in small order of $|E_0|^2$. The second order sin function is used to avoid reducing the amount of holding beam from its initial value. This new modality of injected field can change system's behavior. By introducing the term for injection, we will get various different behaviors from the system, depending on the injection strength and the detuning between the injection and the free running VCSEL. When their detuning has a value similar to the relaxation oscillation frequency of the laser, we often observe new behaviors.

III. RESULTS AND DISCUSSION

Relaxation oscillation is due to movement of the stored energy back and forth between the laser medium and the electromagnetic field confined in the cavity of the laser. Consequently, when a transient current acting on laser steady state (steady state for CS in system and background), in the form of $e^{-\lambda t}$, system would relaxes close to its stable state.

where $\lambda = \gamma \mp i\Omega$ is the perturbation factor. In this process, carrier and photon numbers exhibit an oscillatory behavior with a pseudo period $T_{RO} = 2\pi/\Omega_{RO}$, while the amplitude of the oscillations decays according to $e^{-\gamma t}$ (see Fig. 1) [9].

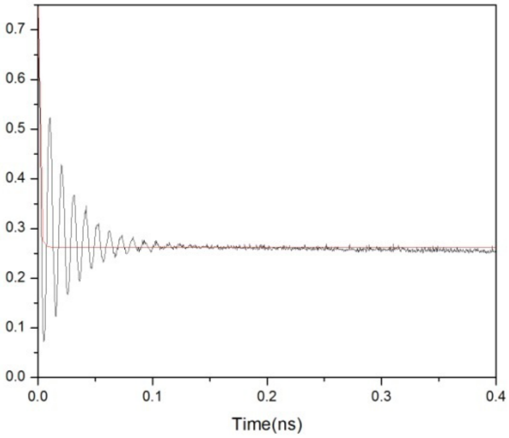

Fig. 1. Damping rate evolution in CS intensity.

By turning the laser on, relaxation oscillation frequency would be computable by calculation of amplitude oscillations before going fixed. Since the life times in VCSELs are considered to be 2.5ps for photons and 1ns for carriers, an order of magnitude of 4.5 GHz is obtained for f_{RO} of a free running laser [10]. A common practice to increase f_{RO} is by operating the laser further above threshold [18].Fig. 2 shows the intensity of the CS for an arbitrary value of injected field which is numerically calculated for different frequencies of modulation. Maximum amplification in CS peak occurs when the AC modulated intensity exactly supports the RO frequency of system. It displays resonance peak at 110 GHz which is system relaxation oscillation frequency in desired injected field. As expected, the RO frequency is greatly enhanced by optical injection in comparison with free running laser. We show now that this large enhancement in RO frequency is also accompanied by a large enhancement of the modulation bandwidth for the CSs that are demonstrated in VCSEL.

It should mentioned here that f_{RO} depends on system parameters and would change by alternation in parameters of system. By varying the holding beam initial value, E_0, the RO frequency of the system would change. We consider the f_{RO} for different injected field and study the response of system. RO frequencies for CS at its peak and of the background in a point sufficiently far from the CS as a function of injected field are shown in Fig. 3. In both cases, we observe a large RO frequency, which is substantially the same for the CS and the background, and decreases slowly as the injected field increase, passing from 114 to about 95 GHz.

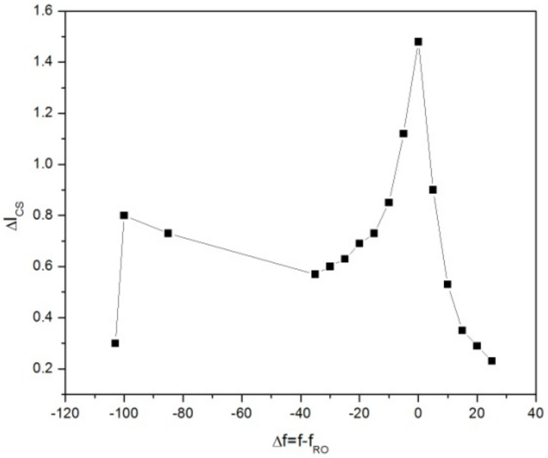

Fig. 2. CS intensity amplification; Parameters are $|E_0|^2 = 0.65$ and $|E_m|^2 = 0.05$.

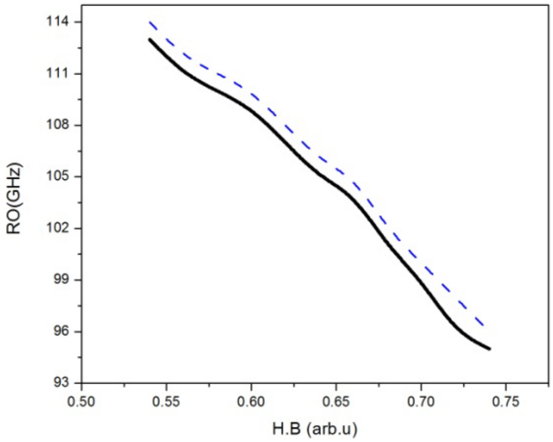

Fig. 3. Relaxation oscillation frequencies as a function of laser holding beam in CS (solid line) and background (blue dashed line) of VCSEL 10% above threshold.

In order to avoid self-oscillating CSs the VCSEL operation is considered 10% above threshold, so that the whole solitonic branch lies in the right of the locking point, as shown in Fig. 4. Homogeneous stationary state of system, which shows bistable feature, results form $\partial_t = 0$ and $\nabla^2 = 0$ in dynamical equations of system. linear stability analyses determines the stable and unstable regions of system, which are shown by solid and dashed lines in Fig.4. Because f_{RO} and damping rate γ are intrinsically linked in a free-running laser in such a way that any increase in f_{RO} is also accompanied by a greater γ. Laser modulation response is one factor affecting overall performance of an optical communication system [19]. Generally, a broad modulation bandwidth requires a combination of high f_{RO} and low γ_{RO} .

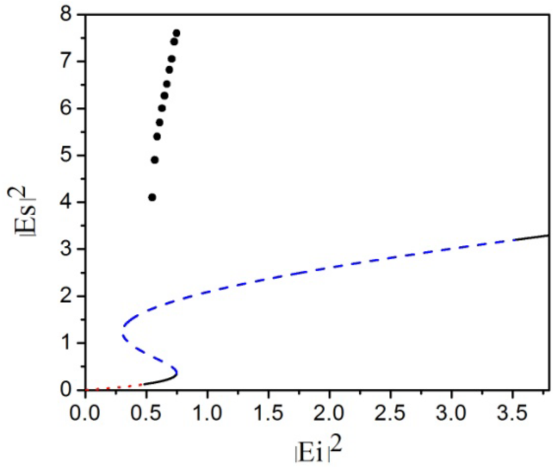

Fig. 4. Homogeneous stationary solution $|E_s|^2$ (solid and dashed lines) and stable branch of CSs (symbols)as function of injected field . This bistable curve is 10% above threshold with nonlinear gain. Red dashed line is the unstable part of the lower branch before the locking point. The negative slope branch and the upper branch are also unstable (blue dashed line). Solid line is stable region and circles show solitonic branch.

In Fig. 5. γ_{RO}/f_{RO} varying with f_{RO} shows that while the ratio initially decreases with increasing f_{RO} , the trend reverses at higher f_{RO}. For the laser configuration considered, eventually increases faster than f_{RO}, after reaching a relaxation frequency of $f_{RO} = 110\,\text{GHz}$. A large γ_{RO} degrades the ability of the laser output to respond to the amplitude variations of the injection current.

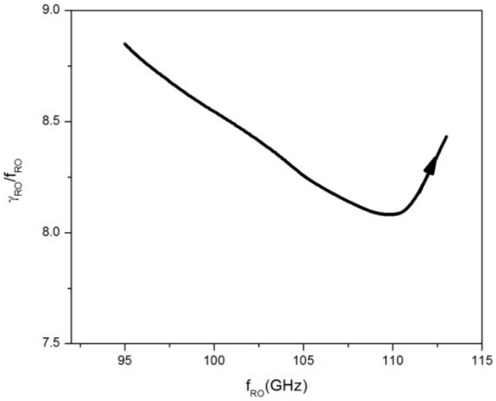

Fig. 5. γ_{RO}/f_{RO} calculated for cavity soliton as function of f_{RO}.

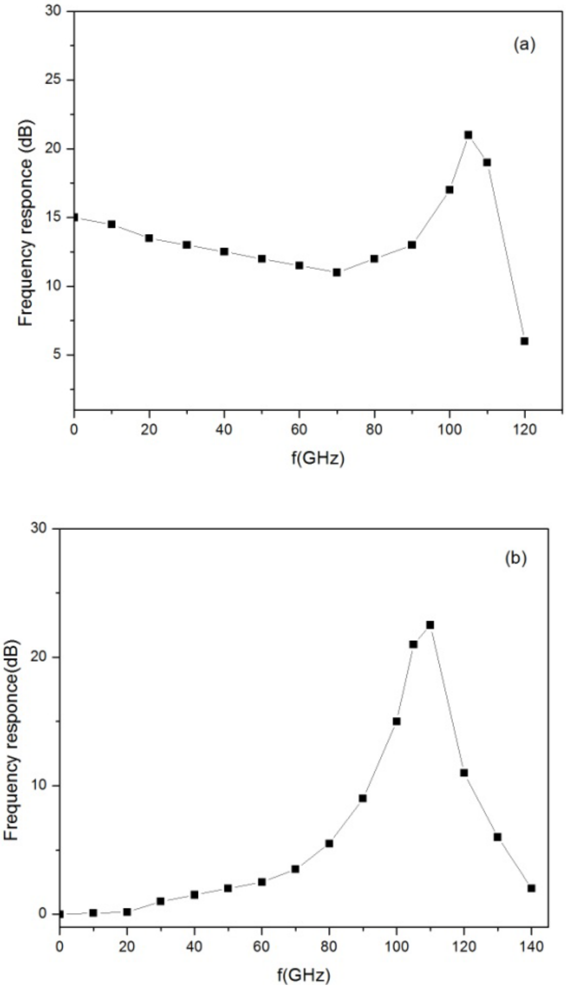

Fig. 6. Frequency response of the CS peak (a) and of the background (b) with $|E_0|^2 = 0.65$ .Parameters same as Fig. 2.

To illustrate the actual improvement in modulation bandwidth, we apply AC modulation to the injected field in the form of Eq. (4). For the value of average injected intensity, $|E_0|^2 = 0.65$ we study the response of the CS and of the background of system.
The results are shown in Figs. 6(a) and (b), respectively. In both cases a large RO frequency, which is substantially the same for the CS and the background is obtained by AC modulation on holding beam. For smaller modulation frequencies, the response in the two points is very different. While the response of the background is sufficient only in a small band around the resonance peak, the CS response is large in whole region from f=0 to the resonance peak and it never drops more than 3dB below the dc limit. Therefore, the CSs enhance greatly the performance of the devise.

IV. CONCLUSION

A high rate of information transmission is one of the key technical properties of secure data communications. The transmitting rate of information signals is a function of the CSs modulation bandwidth, so the enhancement of cavity solitons bandwidth is fundamental to realizing high data rate transmission in cavity soliton laser secure communications. Many studies demonstrated that the modulation bandwidth of laser diodes can be enhanced by external strong light-locking injection. In this work, we study the bandwidth enhancement of the cavity soliton by a semiconductor laser using the holding beam modulation.

The physical mechanism is started from calculation of relaxation oscillation frequency and damping rate of system with their optimum ratio to present a novel method of enhancing the bandwidth of a cavity soliton laser.

Because application of CSs focused mainly on their mobility in the transverse plane and the mobility of them is limited by slowness of carriers [20], here we show that CSs can be modulated in time at rates much faster than their lifetime of carriers, which opens new perspectives for their applications in telecommunication.

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Sahar Ahmadipanah was born in Zanjan, Iran, in 1983. She received BS in Applied physics from Arak University, Arak, Iran (Dec 2000-July 2003), MS in Condensed matter, from Zanjan University, Zanjan, Iran (Sep. 2005-July 2007) and now Ph.D. student in Photonics, Tabriz University, Tabriz, Iran (Sep. 2010). Her research interests are in the area of nonlinear optics and include cavity solitons in VCSELs.

Reza Kheradmand received the Ph.D. degree in physics from the university of Tabriz, Tabriz , Iran in 2005.

He was an ICTP (Abdus Salam International Center for Theoretical Physics, Trieste, Italy) Research Fellow with the University of Insubria, Como, Italy, from 2002 to 2003 and in 2005; he was with the INFM-National Institute for the physics of Matter, Italy. He is currently a researcher with the University of Tabriz. His current research interests include theory of cavity solitons in semiconductor micro resonators, all-optical switching based on optical patterns in semiconductor micro resonators and photonic crystal waveguides.

Franco Prati received his Ph.D. degree in 1993 at the University of Zurich for his studies on spatio-temporal dynamics in lasers. In 1996 he received a permanent position as researcher at the University of Milano and presently he is Associate Professor of Physics of Matter at the University of Insubria.

Franco Prati has been active for almost two decades in the fields of Nonlinear and Quantum Optics. Since 1989 he has participated in several research projects funded by the European Union in the field of Information Technology, as well as two PRINs of the MURST and other INFM and CNR projects. In the last decade his expertise has accumulated in the study of the spatio-temporal dynamics of lasers and related nonlinear optical systems was applied to two particular classes of lasers: the doped fibre lasers and the semiconductor lasers, in particular Vertical Cavity Surface Emitting Lasers (VCSELs).