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Experimental study of resonant activation in a noisy bistable vertical-cavity surface-emitting laser with strong periodic excitation

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An experimental evidence of the phenomenon of resonance activation (RA) in bistable semiconductor vertical-cavity surface-emitting laser (VCSEL) with a high level of internal noise under strong periodic excitation is presented. It is shown that the mean switching period (MSP) between polarization states passes through a minimum depending on the modulation frequency. From comparing frequency dependencies of the MSP and the coefficient of variation it is demonstrated for different conditions that resonance activation and stochastic resonance (SR) occur at different optimal values of the modulation frequency. The influence of the signal amplitude, the level of noise in VCSEL and asymmetry of bistable quasipotential are also experimentally studied. For large enough modulation amplitudes, RA and SR are accompanied by the phenomenon of the mean switching frequency locking.

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The problem of resonant activation in noisy bistable systems with a randomly or periodically fluctuating barrier has attracted considerable attention [1–15]. This problem is important for many applications in physical, chemical, and biological systems. The distinctive feature of resonance activation (RA) is that an averaged residence time or some other quantity associated with activated escape from a metastable state passes through a minimum depending on the correlation time of the stochastic force [1–4] or the frequency of the periodic excitation [7–9]. Evidence of RA has been reported experimentally for a tunnel diode biased in a strongly asymmetric bistable state with a dichotomous noise source controlling the metastable potential [10], underdamped Josephson tunnel junctions with periodical driving [11,13,15] and an experimental system consisting of a periodically modulated bistable colloidal overdamped Brownian dynamics [12] as well as analog simulations [5,6]. Recently, it was theoretically shown that the phenomenon of RA can be observed in a two-mode edge-emitting semiconductor laser under stochastic or periodic modulation of the bias current [14]. The authors in [14] have also concluded that the phenomenon should be observable in the VCSEL case. Many features of the dynamics of a VCSEL operating in a bistable regime can be well described by a model of an overdamped oscillator with a double-well quasipotential for the temporal evolution of the polarization state [16–18]. In the presence of strong enough internal noise or added electrical noise, random switchings between polarization states occur whose statistics obeys Kramers' law [17,19]. A large variety of phenomena such as stochastic resonance [19], noise-induced phase synchronization [20], vibrational resonance [21], and ghost resonance [22] were experimentally observed in bistable VCSELs with a periodic current modulation. Here, an experimental evidence of the phenomenon of resonant activation arising in a VCSEL under a periodic current modulation is presented. In contrast with previous studies where the mean first passage time or residence times were used for a characterization of RA, we employ here the first moment of the return-time distribution or, in other words, the mean period of switchings between two bistable states.

The phenomenon of RA relates to the phenomenon of SR [23] which is a subject of widespread interest in different fields [24–26]. In fact, RA is demonstrated here for the same type of a laser with the periodic modulation where the phenomenon of SR for periodic signals was previously studied experimentally [19]. Therefore, one of the aims of the paper is to find out conditions for both phenomena in these systems. Recent experiments by Schmitt *et al.* [12] with the colloid particle subjected to a time-dependent optical potential, completed by the numerical simulations, have shown that RA and SR occur at different optimal frequencies. In [12], the area under the first peak of residence time distributions as a function of the driving frequency was used to reveal the effect of synchronization due to the phenomenon of SR. In contrast with this measure, we use here a normalized standard deviation (coefficient of variation) to find out effects of synchronization in a driven noisy VCSEL. This statistical measure is an useful indicator for a characterization of coherence [27] and stochastic resonances [26]. From comparing frequency dependencies of the mean switching period and coefficient variation, we demonstrate a manifestation of RA and SR at different optimal frequencies for various amplitudes of the periodic signal, levels of internal noise and asymmetry of a bistable quasipotential in a VCSEL. Besides, in addition to RA and SR we show that for large enough amplitudes of the periodic excitation the phenomenon of the mean switching frequency locking [28] can be observed.

Experiments were performed with a 850 nm VCSEL, operating in the regime of polarization bistability. Schematic of the experimental setup is shown in Fig. 1. The laser was thermally stabilized with an accuracy of a few mK. The dc value of the injection current was chosen to ensure a nearly symmetric configuration of a bistable quasipotential in the middle of the bistability region. The periodic modulation signal from a function generator in the frequency range going from 1 kHz up to 2 MHz with different amplitudes A_m was

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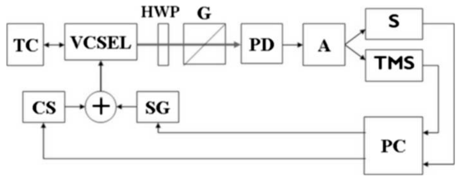

FIG. 1. Experimental setup: CS, current source; TC, temperature controller; SG, signal generator; HWP, half wave plate; G, Glan prism; PD, photodiode; A, 150 MHz bandwidth amplifier; S, USB digital oscilloscope; TMS, two-channel USB time-measuring system with 100 MHz bandwidth of analog inputs; PC, computer.

added to dc current through a bias *T* and subsequently sent to the VCSEL. We used a sample of the laser diode with a strong level of internal noise which causes spontaneous switchings between two polarization states. For some experiments the rate of spontaneous switchings was changed by varying the temperature of the laser diode. Polarization-resolved laser responses were detected with a fast photodetector and recorded by the USB digital oscilloscope interfaced with a PC to store and process the data. Besides, the two-channel USB time-measuring system was also used to measure time intervals between polarization switchings. This system allows one to realize a fast transfer of data to a computer for further data processing with good statistics. The sampling period of this system is 2.5 ns. Because of a peculiarity of the time-measuring system, a sequence of stochastic periods T_S, which are the sum of two consecutive residence times in the first and the second polarization states in VCSEL, is measured directly. The period T_S denotes the time interval between two consecutive switchings in the same direction (e.g., from 1 to 2 or from 2 to 1). Such an approach was used in a number of theoretical works for studying return-time distributions [29–33]. In what follows, we analyze the first two moments of the distribution of T_S, namely, its mean value $\langle T_S\rangle$ and the coefficient of variation (normalized standard deviation) defined as $C_V=\sqrt{\langle T_S^2\rangle-\langle T_S\rangle^2}/\langle T_S\rangle$. For a Poisson process $C_V=1$ whereas for a perfectly periodic process $C_V=0$ [33]. The quantities $\langle T_S\rangle$ and C_V were investigated depending on the frequency and the amplitude of a sinusoidal current modulation at different levels of internal noise and an asymmetry of a bistable quasipotential. They were estimated from a sequence of 10^5 switching periods for each set of parameters. The mean switching period $\langle T_S\rangle$ is used here for the characterization of resonant activation, whereas the coefficient of variation C_V for the frequency dependence of the effects of synchronization.

At first, we performed investigations of the frequency dependence of a laser response to a periodic sinusoidal modulation with a varying frequency and different fixed amplitudes from weak (subthreshold) up to large enough (suprathreshold) values. We evaluated an amplitude of the spectral component S_{max} at the modulation frequency from spectra Fourier transformed time series as a function of the modulation frequency f_m (Fig. 2). Each point was obtained with averaging over 20 signals with 10^5 points. For all modulation amplitudes used in the experiment, the dependence of S_{max} is almost flat for low frequencies and decreases quickly beyond the cutoff frequency f_c. As expected, reso-

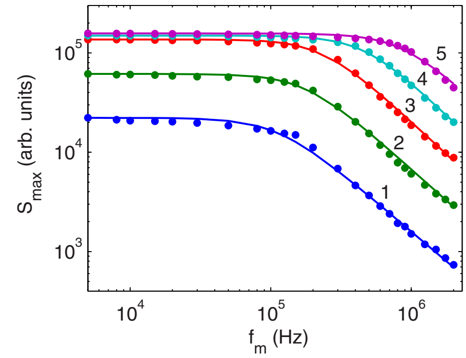

FIG. 2. (Color online) Height of the peak at the modulation frequency in the power spectrum of time series as a function of the modulation frequency is shown for different modulation amplitudes. Solid lines correspond to fitted functions. $A_m=1(1),2(2),3(3),6(4),10(5)$ mV.

nances are not observed under such an excitation. An analysis of experimental data shows that all dependencies presented in Fig. 2 can be formally approximated by a function $H(f)=S^0_{max}/[1+(f/f_c)^p]^{1/2}$, where S^0_{max} is the peak height at the lowest modulation frequency in the power spectrum of time series for a given modulation amplitude, f_c is a cutoff frequency, p is a parameter. For a weak modulation amplitude ($A_m=0.5$ mV), the value of p is close to 2, whereas for higher values $p\approx 2.5$. We found that the cutoff frequency f_c depends on the modulation amplitude as follows: $f_c\approx 23A_m^{3/2}+134$ kHz in the range of $A_m=1-10$ mV. The dependence of f_c on the amplitude testifies that the measurements correspond to the nonlinear regime of excitation. Such a change of the cutoff frequency can be associated with a deformation of the bistable quasipotential by the periodic modulation. As a result, this can lead to a change of the relaxation time in wells. From analysis of the data we also found that in our case the switching threshold up to the frequency $\sim 10^5$ Hz is about 3 mV and rapidly increases with increasing the modulation frequency. This means that our measurements were performed from a completely subthreshold regime (when $A_m=1,2$ mV) up to a suprathreshold regime ($A_m>3$ mV) for low frequencies. In fact, the character of the regime (subthreshold or suprathreshold) depends on the value of the modulation frequency with respect to the cutoff frequency in the frequency dependence of the switching threshold of a bistable system.

In the absence of modulation, most of the time intervals T_S obey an exponential law with a mean value $T_0=\langle T_S\rangle \approx 6.1$ μs. Since the stochastic switching period was measured directly in the experiments, this value T_0 is equal to the double Kramers time T_K for the symmetrical configuration of a bistable quasipotential. When a periodic modulation is applied, the mean value $\langle T_S\rangle$ passes through the minimum depending on the driving frequency as shown in Fig. 3(a) for different values of the driving amplitude. A vertical dashed line in the Fig. 3(a) corresponds to the value of $f_0=1/T_0 \approx 0.5 f_K$, where f_K is the Kramers rate. One can note that the resonance behavior of MSP is clearly seen for all signal amplitudes including also relatively weak periodic signals ($A_m=1,2$ mV) what corresponds to completely subthreshold

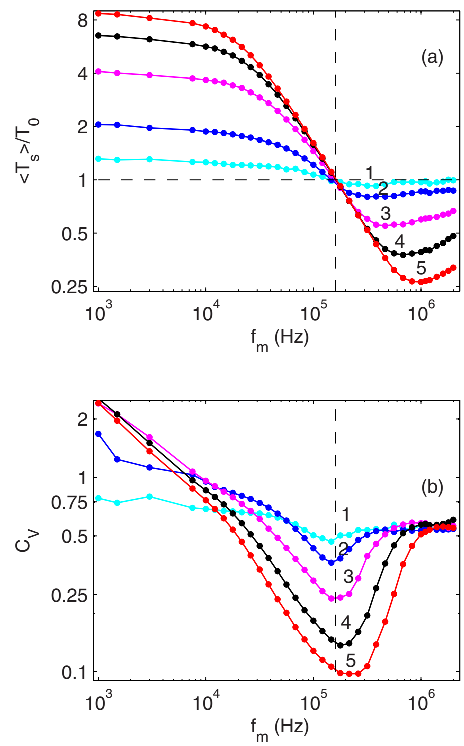

FIG. 3. (Color online) (a) The normalized mean switching period $\langle T_S\rangle/T_0$ and (b) the coefficient of variation C_V as a function of the modulation frequency f_m are shown for different values of $A_m = 1(1), 2(2), 4(3), 6(4), 8(5)$ mV, $T_0 \approx 6.1\times10^{-6}$ s. A vertical dashed line in both figures corresponds to $f_0 = 1/T_0$ (the half Kramers rate).

regime of the excitation. Such a behavior can be associated with the phenomenon of RA. From the behavior of the curve 1 plotted in Fig. 3(a) it can be seen that the MSP tends to the value T_0 as the driving frequency increases. This result qualitatively agrees with the result by Schmitt *et al.* [12]. The resonance frequency f_{RA} shifts to the higher values as the amplitude A_m of the periodic modulation increases while the minimal value of MSP simultaneously significantly decreases. These experimental observations qualitatively agree with numerical results for the case of periodically driven bistable semiconductor lasers presented in [14], where it was shown that the resonance frequency and the mean residence times depend on the driving amplitude for fixed level of noise.

Interestingly enough, all the curves presented in Fig. 3(a) cross each other in the close vicinity of the half Kramers rate (at the frequency $f_m \approx f_0$) which corresponds to a time-scale matching condition for the phenomenon of SR ($\langle T_S\rangle = T_0$). This point approximately separates on the frequency axis two areas of the MSP, namely, $\langle T_S\rangle/T_0 > 1$ for modulation frequencies $f_m < f_0$ and $\langle T_S\rangle/T_0 < 1$ for $f_m > f_0$.

At the same time, the coefficient of variation C_V, shown in Fig. 3(b) for the same amplitudes as in Fig. 3(a), demonstrates a nonmonotonic dependence from the modulation frequency f_m. Such a behavior is typical for the phenomenon of SR for the case of fixed level of noise in a bistable system [26]. For weak modulation amplitudes, the optimal frequency f_{C_V}, for which C_V reaches the minimum, practically

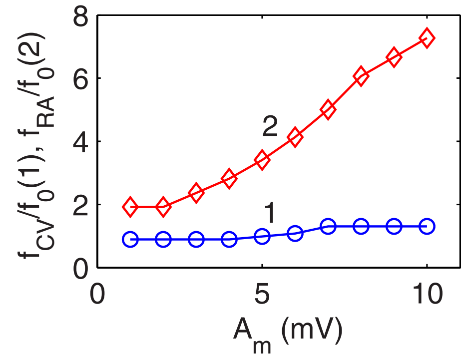

FIG. 4. (Color online) The $f_{C_V}(1)$ and $f_{RA}(2)$ as a function of the A_m. $f_0 = 1.65\times10^5$ s^{-1}

coincides with the half Kramers rate $f_{C_V} \approx f_0 = 0.5 f_K$ within a frequency resolution of the experimental conditions [see in Fig. 3(b) the vertical dashed line and the locations of minima for curves (1), (2), and (3)]. Therefore such a behavior can be considered as a manifestation of the phenomenon of SR, since it occurs when the half period of the forcing equals the Kramers time. However, while SR and RA are observed in the same system with fixed noise under periodic modulation, the optimal values of frequency are different for both phenomena. This result is well agreeing with the results of an investigation of RA and SR in experiments with the colloid particle in a time-dependent optical potential [12].

In Fig. 4 the dependencies of optimal frequencies f_{RA} and f_{SR} are shown as a function of the modulation amplitudes A_m. For weak signal amplitudes the optimal frequency f_{RA} equals the Kramers rate $f_k (f_{RA} \approx 2f_0 = f_K)$, whereas for larger values of A_m the value of f_{RA} significantly increases. Fitting of the experimental data yields the optimal value f_{RA} increasing as $f_{RA} \sim f_c^{0.9}$ depending on the cutoff frequency f_c. One can notice that although optimal values f_{RA} and $\langle T_S\rangle_{min}$ (the minimal value of MSP for a given amplitude A_m) are changed with increasing A_m, their product remains practically constant. In our case, for the given level of noise in the VCSEL $f_{RA}\times\langle T_S\rangle_{min} \simeq 1.56 \pm 0.1$. Simultaneously, the optimal value $f_{SR} \approx f_0$ up to the value $A_m = 5$ mV and f_{SR} slightly increases up to $f_{SR} \approx 1.3 f_0$ for higher modulation amplitudes.

Plots of Fig. 5 show an evolution of the probability density function (pdf) of switching periods T_S for the fixed modulation amplitude $A_m = 2$ mV as the modulation frequency f_m is varied. The dashed line in Fig. 5 corresponds to pdf in the absence of the modulation which obeys an exponential law for most of the switching periods with the mean value $T_0 \approx 6.1$ μs. For a low modulation frequency, when $f_m \ll f_c$ (curve 1 in Fig. 5), the return-time pdf becomes nonexponential due to the continuous changing of the asymmetry of the bistable quasipotential, which occurs adiabatically in this case. Such a change of symmetry in adiabatical regime leads to increasing of MSP as seen from Fig. 3(a). For a high frequency, when $f_m \gg f_c$ (curve 3 in Fig. 5), the system "sees" an average potential. Therefore, the return-time pdf tends asymptotically to the unperturbed potential as the modulation frequency increases. It can be seen in Fig. 3(a) for a weak modulation signal (curve 1) where the curve 1 asymptotically approaches the value $\langle T_S\rangle/T_0 = 1$. In an inter-

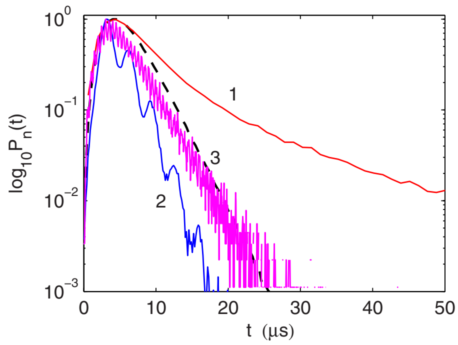

FIG. 5. (Color online) Evolution of the normalized return-time probability density $P_n(t)$ as the modulation frequency f_m is varied, A_m=2 mV. A dashed line corresponds to probability density function in the absence of the modulation. f_m=7.5(1), 300(2), 2000(3) kHz.

mediate case when the modulation frequency is equal approximately to the Kramers rate (for a weak modulation amplitude) we observe a resonant activation (curve 2 in Fig. 5).

For large enough modulation amplitudes, RA and SR are accompanied by the phenomenon of the mean switching frequency locking by the external periodic modulation that is a demonstration of effects of strong synchronization in such systems. This effect has been predicted theoretically and observed experimentally in Schmidt's trigger [25,28], and also in experiments with a bistable VCSEL [20]. This phenomenon manifests itself as a coincidence of the mean switching frequency (MSF) in a stochastic bistable system with the frequency of external modulation for some range of noise intensity. In experiments in [20,25,28], the phenomenon was explored from the dependence of the MSF on the intensity of added noise for different modulation amplitudes. By contrast, a different approach is used here to reveal the locking effects for a fixed level of noise which bases on the frequency dependence of the normalized MSF by the modulation frequency.

In Fig. 6 the dependencies of the normalized MSFs $f_{sn} = \langle f_s \rangle / f_m$ are shown for different modulation amplitudes A_m

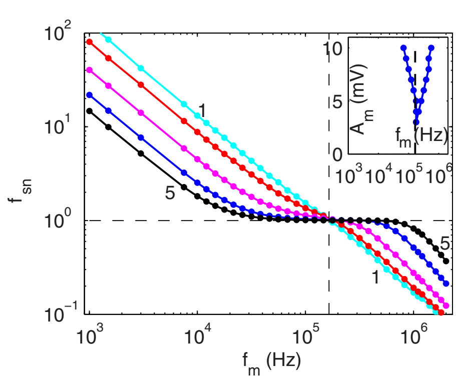

FIG. 6. (Color online) The normalized mean switching frequency f_{sn} as a function of the modulation frequency f_m is shown for different values of A_m [from (1) to (5) A_m=1,2,4,7,10 mV]; $T_0 \approx 6.1 \times 10^{-6}$ s. A vertical dashed line corresponds to $f_0 = 1/T_0$ (the half Kramers rate). Inset: the synchronization region for a fixed level of internal noise in VCSEL.

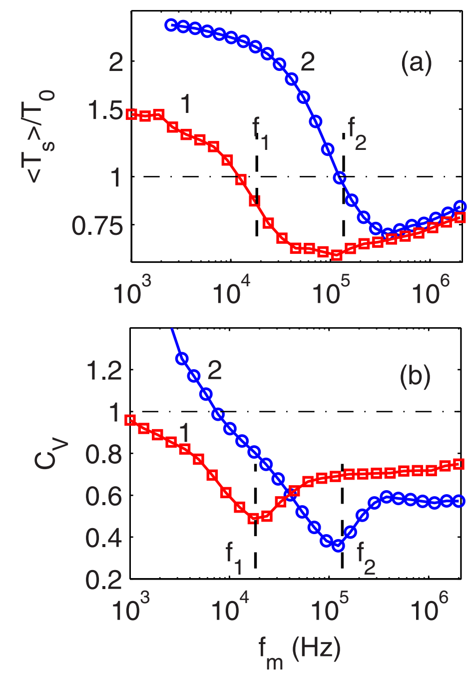

FIG. 7. (Color online) (a) The normalized mean switching period $\langle T_S \rangle / T_0$ and (b) the coefficient of variation C_V as a function of the modulation frequency f_m are shown for two different levels of internal noise in VCSEL which is characterized by two different values of MSF: $f_1 \approx 18$ kHz (1), $f_2 \approx 135$ kHz (2). A_m=2.5 mV.

(where $\langle f_s \rangle = 1/\langle T_S \rangle$). In the absence of the periodic modulation as well as for a weak periodic modulation the dependence of f_{sn} versus f_m is almost linear. As the modulation amplitudes increase one can clearly see an appearance of intervals of the modulation frequencies in which $f_{sn} \approx 1$. This means that the mean switching frequency approximately equals the modulation frequency what testifies the locking effect by external periodic modulation. Making a series of such measurements with different amplitudes one can find a synchronization zone in the parameter space (modulation amplitude A_m, modulation frequency f_m) in which the MSF is locked by the periodic forcing as shown in the inset of Fig. 6. In order to find the boundaries of the synchronization region, the condition $0.99 < f_{sn} < 1.01$ was used. One can see from Fig. 6 that the synchronization zone is located around the value f_{SR} (shown by a dashed line) and has some threshold value A_{th} (in our case $A_{th} \approx 3$ mV).

The value of the resonance frequency and the mean residence time in the phenomenon of RA for the periodically driven overdamped bistable oscillator depend also on the level of noise in the system as shown in Refs. [8,9]. Figure 6(a) presents the normalized value of MSP ($\langle T_S \rangle / T_0$) depending on the modulation frequency for two different levels of noise in the VCSEL. It can be seen from Fig. 7(a) that both characteristics strongly depend on the level of noise. The same can be noted concerning the coefficient of variation C_V shown in Fig. 7(b). In addition, one can notice that the optimal values (f_{RA} and f_{C_V}) are located in different parts of the frequency axis. At the same time the optimal frequencies for C_V coincide with the half Kramers rate shown in Fig. 7 by dashed lines and denoted by f_1 and f_2. In case presented

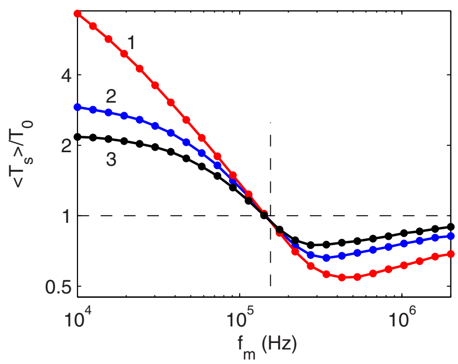

FIG. 8. (Color online) The normalized mean switching period $\langle T_S\rangle/T_0$ as a function of the f_m is shown for three different type of periodic signals: (1)—square-wave; (2)—sine-wave; (3)—saw-tooth; A_m=3 mV. A vertical dashed line corresponds to $f_0=1/T_0$ (the half Kramers rate).

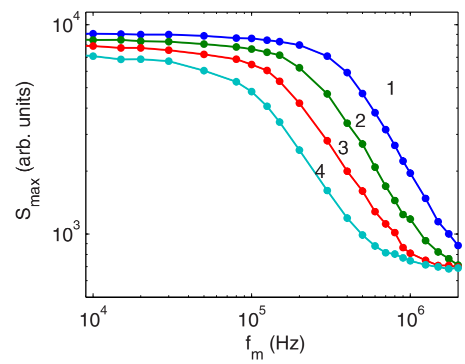

FIG. 9. (Color online) Height of the peak at the modulation frequency in the power spectrum of time series as a function of the modulation frequency is shown for different level of asymmetry ΔV. $\Delta V=0(1),1(2),1.5(3),2(4)$ mV.

above the noise intensity was controlled by a variation of the temperature of the laser diode from ≈ 18 °C (f_1) to ≈ 23 °C (f_2).

The previous results were obtained with the use of a sinusoidal periodic modulation of the pump current. Numerical [9] and experimental [12] investigations have shown that the shape of the periodic signal may affect the phenomenon of RA. In Fig. 8 an efficiency of the modulation on the manifestation of RA is compared for different types of periodic signals in the VCSEL. It can be seen graphically in Fig. 8 that the values of the resonance frequency f_{RA} and the minimal switching period $\langle T_S\rangle_{min}$ depend on the type of the signal. The maximal effect is observed with the use of square-wave periodic signals for which the effect of RA appears most clearly (the curve 1 in Fig. 8). Analogous results were experimentally demonstrated in Ref. [12] where it was shown, that a square-wave periodic signal leads to smaller values of the mean residence time than with a sinusoidal modulation. One of the possible explanations of the different efficiency can be associated with the fact that switching thresholds are different for all the types of signal. The lowest threshold is observed for the square-wave shape while the highest for the saw-tooth shape for all frequencies used in the experimental investigations. This means that a relative amplitude of the signals are different for all the types. As a consequence of this difference, the effect is maximal for the largest relative amplitude. It should be also noted that analysis of the behavior of the coefficient of variation has shown that the strongest synchronization occurs at the frequency $f_m \approx f_0$ for all types of the signal.

Finally, we demonstrate how the static asymmetry of a bistable quasipotential affects the phenomenon of RA. The appearance of the static asymmetry in a double-well potential in a noisy bistable system leads to the splitting of residence times, so the system cannot be characterized in this case by a single Kramers rate as in the purely symmetrical case. Instead, the MSP can be used in the asymmetrical case for a characterization of effects of synchronization in stochastic bistable systems [31]. The level of asymmetry ΔV is defined here as $\Delta V=V-V_0$, where V is an actual value of the applied voltage and V_0 is the applied voltage corresponding to the symmetrical quasipotential. In these experiments, the applied voltage was changed with a step of 0.5 mV resulting in the control of the level of asymmetry of the quasipotential [16]. In the absence of the modulation the MSP (T_0) nonlinearly increases with the rise of ΔV. For instance, adding of ΔV=2 mV results in an increase of the MSP from $T_0 \approx 6.1$ μs up to $T_0 \approx 40.6$ μs. Besides, the static asymmetry leads to a change of the frequency response to the periodic modulation as shown in Fig. 9 for different values of the asymmetry ΔV. As in the symmetrical case no resonances were observed for these experimental conditions. At the same time, one can note that the cutoff frequency f_c changes significantly as the level of asymmetry increases, for instance, from $f_c \approx 340$ kHz(ΔV=0) up to the value $f_c \approx 80$ kHz for ΔV=2 mV.

In Fig. 10 the MSP and C_V are shown as a function of the modulation frequency for different levels of the asymmetry ΔV. It can be seen that optimal values of f_{RA} and f_{C_V} are shifted to the lower values as ΔV increases (Fig. 10). Such a shift can be associated with a simultaneous effect of two factors, namely, an increase of T_0 and a diminution of the cutoff frequency f_c for the fixed level of noise and signal amplitude. Analysis of data has shown that in this case $f_{RA} \approx 2.5 f_0$, what is slightly higher than the Kramers rate. At the same time, the value f_{C_V} coincides very closely with the value f_0, what corresponds to a time-scale matching condition for SR in an asymmetrical case [31]. Similar to the symmetrical case, the product of optimal values f_{RA} and $\langle T_S\rangle_{min}$ remains practically constant with increasing ΔV. In this case, $f_{RA}\times\langle T_S\rangle_{min} \simeq 1.52 \pm 0.1$ what practically coincides with the symmetrical case for the same fixed level of noise. In fact, this product remains almost constant for weak level of asymmetry of quasipotential and the sufficiently large diving amplitude when the amplitude much larger than the level asymmetry. In addition, one can also remark that an increase of degree of a static asymmetry leads to a degradation of the effect of the mean switching frequency locking.

Before we conclude, some discussion concerning the behavior of the coefficient of variation presented in Figs. 3(b), 7(b), and 10(b) may be made for limit cases. From these plots one can see that for the frequencies which are much lower than the half Kramers rate, the coefficient of variation

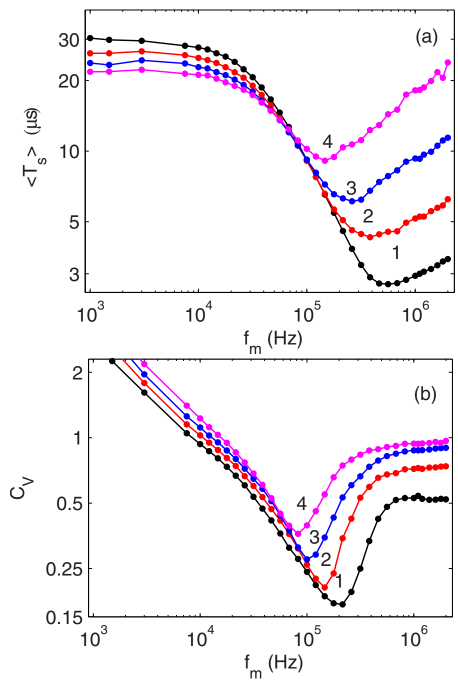

FIG. 10. (Color online) (a) The mean switching period $\langle T_S \rangle$ and (b) the coefficient of variation C_V as a function of the modulation frequency f_m are shown for different levels of asymmetry $\Delta V = 0(1), 1(2), 1.5(3), 2(4)$ mV. $A_m = 5$ mV.

can reach the value larger than 1 (even much larger). The effect becomes more and more apparent with increasing the driving amplitude [Fig. 3(b), curves 3–5], the level of internal noise [Fig. 7(b), curve 2] or the degree of asymmetry of quasipotential [Fig. 10(b)]. Such a strong rise of C_V can be explained by the appearance of the bursting effect which is observed in the temporal behavior of the laser intensity. In this case, most of polarization switchings occur when the quasipotential periodically passes through a symmetrical configuration, causing the strong variability of the switching periods. The fact that the effect of bursting leads to the values of C_V larger than 1, was noted in Ref. [33] where this aspect was studied theoretically for a stochastic bistable system driven by dichotomous noise. In the opposite case, when the driving frequency is much higher than the half Kramers rate, for the fixed level of noise in the laser the value of C_V does not depend on the driving amplitude and tends to the value of C_V for the unperturbed quasipotential [Fig. 3(b)]. At the same time, the value of C_V depends weakly on the level of internal noise. An increase of f_0 from $\approx 1.7 \times 10^4$ to $\approx 1.65 \times 10^5$ s^{-1} causes the value of C_V to decrease from ≈ 0.75 to ≈ 0.6 [Fig. 7(b)]. A stronger dependence occurs with increasing the degree of asymmetry. For instance, for $\Delta V = 2$ mV the value of C_V approximately reaches unity [Fig. 10(b), curve 4] that corresponds to the homogeneous Poisson process.

To conclude, we have presented experimental evidence of the phenomenon of resonant activation in VCSEL operating in the regime of polarization bistability for the case of both nearly symmetrical and asymmetrical configurations of a bistable quasipotential. The phenomenon of RA appears as a minimum in the nonmonotonic dependence of the MSP on the modulation frequency. We have also demonstrated for different experimental conditions that resonant activation and stochastic resonance occur for different optimal frequencies in a bistable system with a fixed level of noise. Besides, we have shown that the frequency dependence of the mean switching frequency locking can be observed in a noisy bistable system in parallel with RA and SR for sufficiently large modulation amplitudes.

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